

Howard Hill

M.F. "33"

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- 370
1. Sliding drag & parasite curve
 2. 1. = 2. of Total drag

Jules D. Campbell

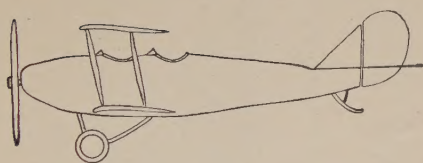
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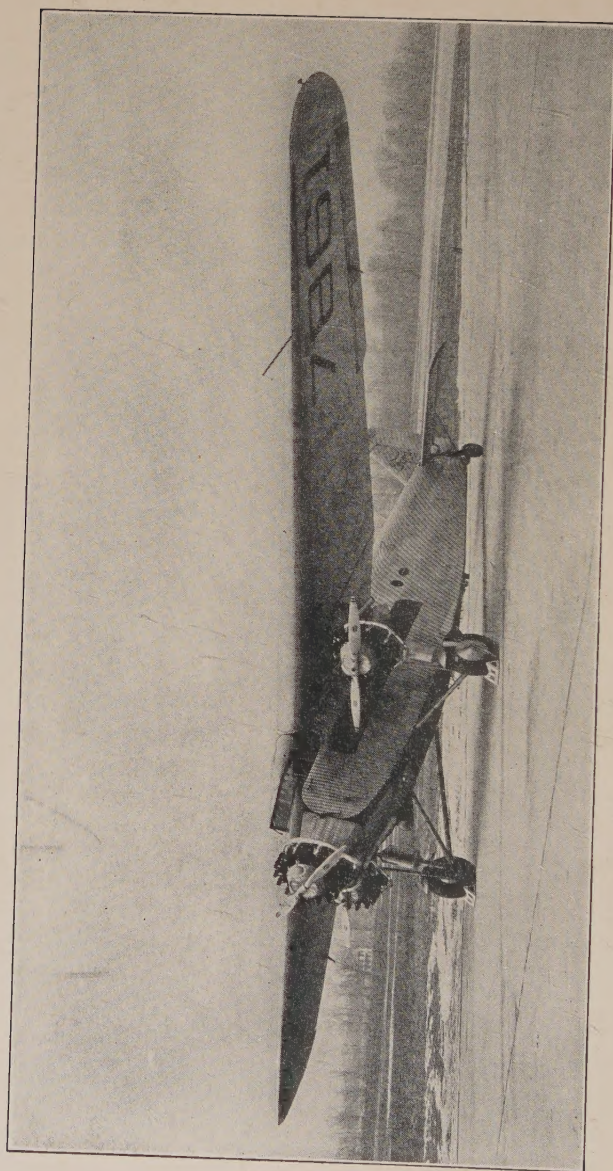
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$$\frac{v^2}{2gs} = \left(\frac{F}{W} \right) = \text{Load factor}$$

THE AIRPLANE





(Frontispiece)

"FORD" TRI-MOTOR TRANSPORT AIRPLANE

THE AIRPLANE

*A practical discussion of the principles
of airplane flight*

BY

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Airplane Characteristics, 1918

The Air Propeller, 1919

The Airplane, 1920

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PREFACE

THE first thirteen chapters of this book comprise material that has appeared in earlier editions, very much enlarged, however, and rewritten in view of the experience of many readers who have used the book as a text and as a practical work of reference. The material for the last five chapters now appears for the first time and completes the plan of the author to present a well-rounded treatment of the airplane covering the general principles of airplane flight in a manner that is simple and at the same time reasonably complete and accurate.

The author has benefited by the kindly criticisms of those who have used the earlier editions and has been spurred on in his attempt to meet the needs of flyer and designer on the one hand and of the general reader on the other. The interest shown in the book by members of the aeronautic profession, as well as by those whose point of view is scientific or educational rather than practical, gives assurance that the book will continue to find a useful field.

The author has attempted, not only to bring all the discussion completely up to date, by addition here and by omission or change there, but to give the book a balance and completeness by rounding out certain parts, before only touched upon, which are needed for an understanding of the airplane in all its aspects.

It has been the author's purpose to present the principles of airplane sustentation and stability and the characteristics of the airplane in flight in a way that is direct and simple, and at the same time thorough, without the use of higher mathematics. He has aimed to meet the needs not only of the flyer and designer, for whom the book is primarily intended, but of students and engineers and others who have only a general interest in aviation. Logical sequence, rather than historical development has been kept in mind. Military uses of the airplane, as

well as its history, are left to others. Stress is laid on that which is vital, while unessentials, so far as possible, have been omitted or only touched upon.

A full discussion is now included of the airplane engine and its latest developments. This, together with the complete analysis of the air propeller, with the description now included of various types of airplane, completes the discussion of the airplane proper. The comprehensive chapter on airplane instruments shows some of the problems that confront the pilot, while the chapter on outstanding problems indicates the present line of development of the art of airplane flight.

For their courtesy in allowing the use of illustrations of certain airplanes and airplane engines, the author desires to thank the following companies: American Aeronautical Corporation, Bellanca Aircraft Corporation, Chance Vought Corporation, Curtiss Aeroplane and Motor Company, Inc., Ford Motor Company, Packard Motor Car Company, Pitcairn Aircraft Corporation, Wright Aeronautical Corporation. He wishes also to thank the editorial and manufacturing staffs of D. Van Nostrand Company for their kind coöperation.

F. B.

CORNELL UNIVERSITY, ITHACA, N. Y.
JULY 1, 1930

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CHAPTER I

SUSTENTATION

Any body, to remain at the same altitude or to move in a path of constant altitude in a fluid medium, must have a sustaining force or **sustentation**. Otherwise a change in altitude will result. Sustentation is, therefore, the first essential of sustained flight.

Aircraft can be classified in general as being **lighter-than-air** or **heavier-than-air**. Balloons and dirigibles are examples of lighter-than-air craft. The volume of air displaced by the gas bag of such craft is heavier than the weight of the bag and the gas in the bag. The difference, between the weight of the air displaced and the combined weight of gas bag and gas, is the amount of sustaining force or sustentation the gas bag affords for the other parts of the balloon or dirigible. Aircraft of this type can rise, even in still air, and will remain at a constant altitude if the sustaining force, as described above, is exactly equal to the weight of the craft.

The airplane is the only heavier-than-air craft that has been successfully developed beyond the experimental stage at present. It obtains forward motion by means of a power plant and a propeller. It obtains sustentation by means of wings or surfaces which, by virtue of the forward velocity of the airplane, encounter the air and force it downward in passing. The upward reaction of the air to this downward deflection affords the means by which the airplane rises and maintains flight.

Various heavier-than-air craft with other means of obtaining sustentation have been attempted. Among these are the **ornithopters**, having wings which flap, like those of a bird, forcing the air downward and backward. Of a quite different type are the **helicopters**, in which sustentation is obtained by means of propellers mounted on vertical shafts. These propellers force the air

directly downward; and the machine, if successful, should rise vertically. Of these two types, none, as yet, have been successfully developed beyond the experimental stage because of the mechanical difficulties encountered in design.

The latest development has been the **autogiro**, invented by Senor de la Cierva, of Spain. This machine is a combination of airplane and helicopter in that it has a propeller on a horizontal shaft for obtaining forward motion and a set of blades on a vertical shaft for obtaining its sustentation. A further description of this machine will be found in a following chapter. The discussion in the next few chapters will be limited to the airplane.

Stability, a second essential for sustained flight, will be treated in a later chapter.

Any volume of air, which has been forced or deflected downward by an airplane wing, is lost to the wing and therefore cannot give any more upward push to the wing. To maintain this upward push, called lift, it is necessary that new air be encountered and deflected by the wing continuously. Therefore, it is necessary that the airplane move rapidly through the air to maintain sustentation, as then only can new air be continually encountered and deflected. An understanding of sustentation will best be gained by a consideration of the pressure exerted by the air upon flat and curved surfaces moving rapidly with relation to it.

FLAT PLANE PERPENDICULAR TO AIR-STREAM

We will first consider the force on a flat plane perpendicular to an air-stream.

Force varies as square of velocity. — If a thin plate or plane, say a book cover or the cover of a cigar box, is held out from a moving automobile — well away from the body and windshield — so that the air-stream strikes the plane perpendicularly to its surface, as in Fig. 1, a force is felt that is small at low speeds but which increases very rapidly as the speed increases. In fact, if accurate

measurements were made, it would be found that when the speed is doubled the force becomes four times as great, in other words that the force on the plate varies as the square of its velocity through the air.

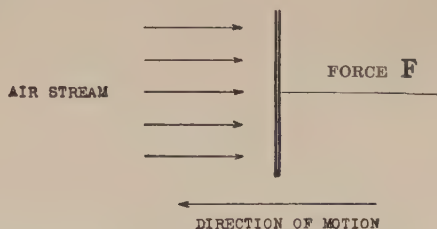


FIG. 1. Force on a flat surface.

Furthermore, this same relation would be found to be true if the plane were held still in a wind or in the air from a blower, and so it is seen that the force depends not upon the absolute velocity of the plane or of the air but upon their *relative* velocity, as the air-stream strikes the plane. This is on account of the great mobility of the air particles, the effect being the same whether the air is stationary or moving. The law of the "square-of-the-velocity," although not a general law that holds in any fluid and for all velocities, may be taken as practically true in air throughout the range of airplane velocities.

Force varies with plane area. — By using planes of different areas, it would be found, likewise, that the force on the plane increases with the plane area and (practically) in direct proportion to the area; for example, an increase of ten per cent. in area is accompanied by an increase of ten per cent. in force on the plane. This relation, however, must be considered as only approximate, particularly when the planes compared differ greatly in shape or area.

General law. — The force F , upon a surface S , normal to an air-stream with velocity V , may accordingly be expressed by the following law: —

$$F = KSV^2.$$

Here K is a number or coefficient, the value of which depends upon the units used.¹ When the area S is given in square feet, the velocity V in miles per hour and the force F in pounds, a practical value for the coefficient K , that has been determined experimentally, is 0.003 for air at normal density; that is,

$$F = 0.003 SV^2.$$

The force per square foot of surface is thus seen to be 1.2 pounds at a velocity of 20 miles per hour, 4.8 pounds at a velocity of 40 MPH., 19.2 at 80 MPH., etc.

Metric units.— When V is velocity in meters per second, S the area in square meters and F the force in kilograms, the value of K is 0.075. To get K in English units of pounds, square feet and miles per hour, multiply K for metric units by 0.0408.

Variations in K . — The value of K is not strictly a constant. It varies directly with the density of the air, decreasing, therefore, with altitude, as discussed later, and changing somewhat from day to day. It varies, also, with the size and shape of the surface. The values given above ($K = 0.003$ in English units, $K = 0.075$

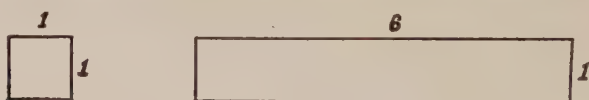


FIG. 2. Square with aspect ratio 1; and rectangle with aspect ratio 6.

in metric units) are for a square surface, 0.50×0.50 meters, in air of normal density. For squares of different sizes, experiments of Eiffel gives values for K as follows:—

Length of side	.15m.	.375m.	.500m.	.707m.	1.00m.
Value of K	.066	.0716	.0746	.0772	.0789

¹ Thus, when F is expressed in ounces per square foot, the numerical value of F , and so of K , is 16 times as great as when F is expressed in pounds per square foot.

For rectangles of equal area (0.225 m.^2) and with different aspect ratios (the aspect ratio is the length divided by width, see Fig. 2) Eiffel gives:—

Aspect Ratio	1	3	6	10	20	30	50
Value of K	.066	.0705	.0725	.0755	.0885	.092	.097
$K_R \div K_S$	1.	1.07	1.10	1.145	1.34	1.40	1.47

The last line, $K_R \div K_S$, is the value of K for a rectangle divided by the value of K for a square. The percentage increase in K with increase of aspect ratio, shown in the last line, will hold approximately for rectangles of other areas, for the effect of aspect ratio is almost independent of size of surface.

Somewhat different values hold for circular discs and other shapes. Considerable experimental data must be gathered before the *precise* value of K can be determined for a surface of any size and shape. Meanwhile the value 0.003 (English system) or 0.075 (metric system) will prove practically useful, it being borne in

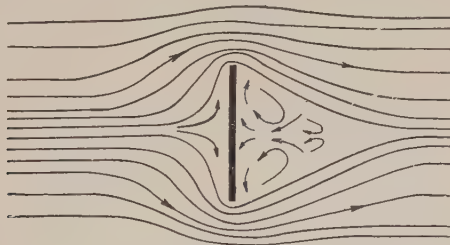


FIG. 3. Turbulent region and rarefaction back of plane.

mind that this value is only an approximation and that a closer value should be sought whenever it may be deemed desirable.

Eddies back of plane. — When a plane encounters an air-stream, there is a compression of the air on the front face of the plane. Immediately back of the plane there is a rarefaction, so that back of the plane air currents are set up that swing around toward its rear surface. These air currents may be felt, by one riding in an

open trolley car or in an automobile behind a wind-shield, as a wind on the back of the neck.

These air currents are, in a crude way, visualized in Fig. 3. Back of the plane and near the edge is a turbulent region with complex eddy currents of air. These no doubt have a material effect upon the value of K , so that it is not surprising that K has different values for surfaces of different shapes and sizes, for in these the length of edge and the eddy-current effects are not proportional to the area.

Methods of experimenting. — Experiments on the air resistance of different surfaces or bodies may be made in various ways. The necessary velocity of the body relative to the air may be obtained by dropping it from a suitable tower or other height (employed by Eiffel), by carrying it on a fast moving vehicle, by carrying it at the end of a long rotating arm (employed by Langley), by exposing it to a natural or artificial wind, and finally by carrying it through the air in airplane flight.

The most convenient and approved method now in use is to expose the body to an artificial wind in a *wind tunnel*, first used by Eiffel ² and now used in all aerodynamic laboratories. Air is forced through such a tunnel by means of a powerful fan; the body to be studied is held stationary, being attached to suitable devices for measuring the force and, in case of oblique surfaces, for “weighing” the vertical as well as the horizontal component of the force.

In such a tunnel can be tested not only surfaces or bodies of various kinds, including wing sections, but even complete airplanes in model size; and it is important to note that the performance of wings and airplanes in flight is found to agree remarkably well with wind-tunnel tests. Certain experts on aeronautics have expressed the opinion that the camera or kinematographic tests for airplanes will displace the use of the wind tunnel for experimental work in

² Eiffel's experiments are beautifully described in his book “The Resistance of the Air and Aviation,” translated into English by J. C. Hunsaker.

the future. More conservative engineers insist that a thorough wind tunnel test should be made of every new airplane, in model form, before allowing pilots to risk their lives in them.

FLAT PLANE OBLIQUE TO AIR-STREAM

Let us next consider the action of a flat plane at an oblique angle with the air-stream; such a consideration will show at once the source of the sustaining force in an airplane.

Lift of an oblique plane. — If a plane be held so as to form an angle α (called the **angle of attack**) with the air-stream or “relative

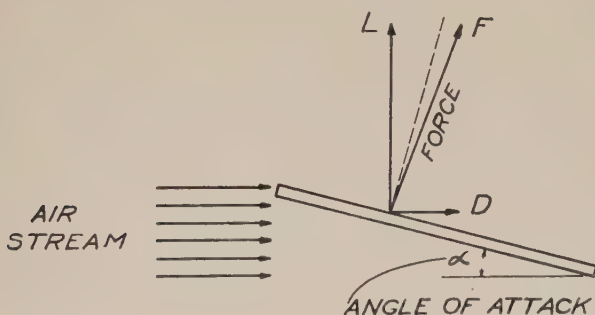


FIG. 4. Vertical and horizontal components of force F on oblique plane.

wind,” as in Fig. 4, it will be seen that the force F of the air against the plane has two components:³

³ These two components are horizontal and vertical in normal horizontal flight. More accurately defined, lift is the component of force that is perpendicular to the air-stream and that lies in the plane of symmetry of the machine; this plane is vertical as long as the machine does not roll. Lift is accordingly vertical in normal flight, but becomes inclined when the machine is inclined, as shown in Fig. 4a. Wing-drag is, in all cases, the component of force that is in the direction of the air-stream.

It is recommended by the National Advisory Committee for Aeronautics that “wing resistance” and “drift,” sometimes used as designations for wing-drag, be abandoned; see “drift” in Glossary, Appendix. But the initial letter D , in such common use, may well be retained as a symbol for drag; likewise, K_D formerly called coefficient of drift, may be retained as the coefficient of drag. See paragraph on *Terminology*, Chapter III.

A component perpendicular to the air-stream, called **lift**, commonly designated by the letter L , tending to force the plane in a direction at right angles to the air-stream.

A component or dynamic resistance parallel to the air-stream (called **wing-drag** or **wing resistance**), commonly designated by the letter D , tending to force the plane *backward* in the direction of the air-stream.

These components may be observed by blowing upon a card held in the hand oblique to the air-stream, or by moving the hand — slightly inclined — rapidly through water; in the latter case the upward lift may be distinctly felt.

It is the lift that holds an airplane up in flight, i.e., that gives sustentation; for an understanding of the airplane, therefore, a knowledge of what determines the lift is essential. Clearly for horizontal flight the lift must be just equal to the weight of the machine, otherwise the machine will either ascend or descend, — discussed later under *climbing* and *gliding*. The problem of horizontal flight is, therefore, the problem of securing a lift equal to the weight. As discussed later, this lift is better obtained from a “cambered” wing (i.e., a wing that is slightly curved from front to back) than from a flat plane.

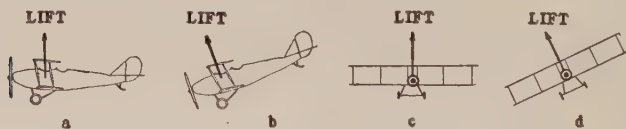


FIG. 4a. Lift is inclined when machine is inclined.

In order to get the lift, the plane or wing must move rapidly through the air. But in order to move the plane or wing through the air it is necessary to overcome the wing-drag and this is done by the *thrust* from the propeller. To drive the propeller, so as to

The use of “angle of incidence i ” for “angle of attack” is abandoned; as angle of incidence now refers to the mechanical setting of the wing.

obtain this thrust, it is necessary to have *power*. Obviously it is desirable to have the wing-drag small, necessitating small thrust and small power, and to have the lift large so that the machine can sustain not only itself but some load in addition. But it is impossible to have the lift without the wing-drag, and the wing-drag has aptly been described as the price paid for the lift.

Variation of lift and wing-drag with angle of attack. — Highly important is it to know how the values of lift and wing-drag vary

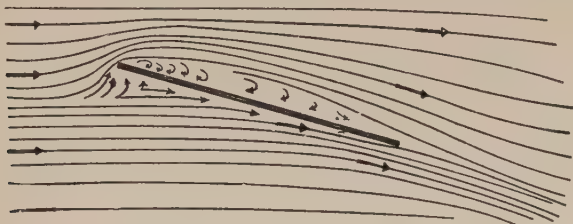


FIG. 5. Flow of air past oblique plane, showing turbulent region back of entering edge and the downward deflection of air after leaving the plane.

as the angle of attack is changed. This information cannot well be derived theoretically on account of the complexity of the problem, — due in part to the eddy currents in the turbulent region back of the entering edge, as indicated in Fig. 5. The information, however, has been found experimentally.

The force F , the lift L , and the wing-drag D all vary directly as the area S , of the plane or wing, and as the square of the velocity V ; that is,

$$\text{Force} = F = K_P SV^2;$$

$$\text{Vertical component or lift} = L = K_L SV^2;$$

$$\text{Horizontal component or wing-drag} = D = K_D SV^2.$$

We are particularly interested in the two components L and D ; also in the two coefficients,⁴ K_L called the **coefficient of lift** and K_D called the **coefficient of wing-drag**. Those coefficients have differ-

⁴ The absolute coefficients used by the National Advisory Committee for Aeronautics are non-dimensional and independent of the units used so

ent values for each angle of attack. Their values, furthermore, will depend upon the units used and upon the density of the air.

The values of these coefficients that will give lift and wing-drag

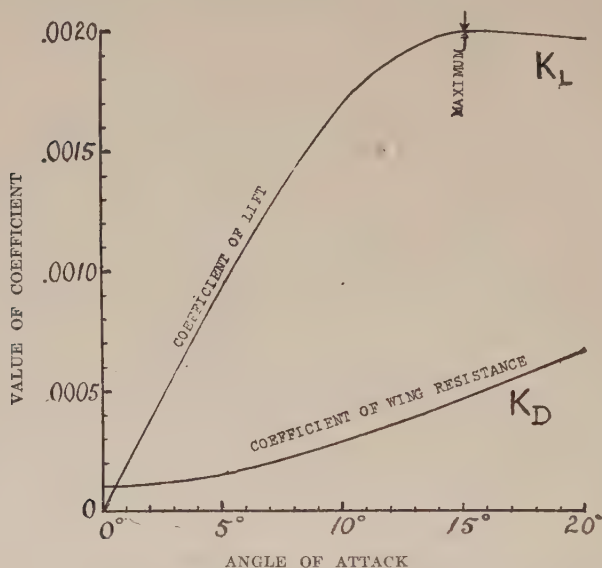


FIG. 6. Coefficient of lift K_L and coefficient of wing-resistance or drag K_D for flat rectangle at different angles of attack; aspect ratio, 6, *i.e.*, length $\div$ width = 6, as in Fig. 2.

long as they are used consistently. The formulae for lift and drag using the absolute coefficients are as follows:

$$L = C_L \times q \times S;$$

$$D = C_D \times q \times S.$$

L is the lift in pounds or kilograms.

D is the drag in pounds or kilograms.

C_L is the absolute lift coefficient.

C_D is the absolute drag coefficient.

q is the dynamic or impact pressure of the air and is equal to $\frac{1}{2}\rho V^2$, V being the true air speed in feet per second or in meters per second. ρ is the density of the air in mass per unit volume. It is equal to the specific weight of air, in pounds per cubic foot or in kilograms per cubic meter, divided by the acceleration due to gravity, in feet per second per second or in meters per second per second.

S is the area under consideration in square feet or in square meters.

The absolute coefficients can be changed to the coefficients used in this text if they are multiplied by 0.00255.

in pounds, for different angles of attack; when S is in square feet and V is in miles per hour, are shown by the curves in Fig. 6. These are plotted from data by Eiffel⁵ for a flat rectangle with an aspect ratio 6.

For small values of angle of attack, it will be seen that the coefficient of lift increases nearly uniformly, in proportion to the angle of attack; if the angle is doubled, the coefficient of lift is approximately doubled. After reaching a maximum value (in this case about 0.002) the coefficient decreases somewhat irregularly,⁶ becoming zero at 90° angle of attack.

This maximum value is only two-thirds as great as the maximum value obtained by a cambered wing; see Fig. 11.

The coefficient of wing-drag also increases more or less uniformly with angle of attack and reaches a value of about 0.003 at 90° ; but in no case is K_D zero, even at zero angle of attack.

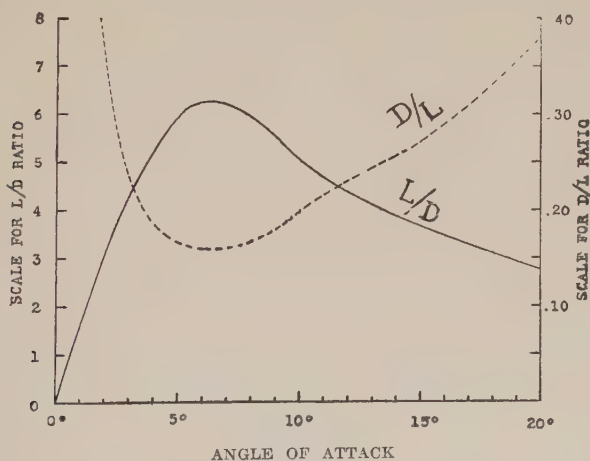


Fig. 7. Curves showing L/D ratio and D/L ratio for flat rectangle; aspect ratio, 6.

Lifting efficiency or L/D ratio. — The ratio of lift to wing-drag is frequently referred to as the **lift-over-drag ratio** or the **L/D ratio**,

⁵ "Resistance of the Air," p. 122; size of rectangle 90×15 cm.

⁶ After 20° , K_L increases slightly, having by Eiffel's data the same value

or as the **lifting efficiency**, or as the **effectiveness** of a plane or wing, and this ratio is of much significance. As it is desirable to have L large and D small, it is obviously desirable to have the L/D ratio as large as possible. It is seen that the L/D ratio is equal to $K_L \div K_D$ values for which are obtained from the curves in Fig. 6.

The values of the L/D ratio for a flat rectangle with aspect ratio 6, thus obtained from Fig. 6 for different angles of attack, are shown in Fig. 7. The maximum value for L/D is here seen to be a little over 6 at an angle of attack of 6° , — a rather poor lifting efficiency compared with an L/D ratio 16 or more for a cambered plane.

In Fig. 7, the values are also shown for D/L (see dotted curve); but, as these values approach infinity when L approaches zero, they are not so convenient to use. It is more usual, therefore, to make use of the L/D ratio.

In the case of a theoretical plane with a perfectly smooth surface, the force F would be perpendicular to the surface, so that D/L would be the tangent and L/D the cotangent of the angle of attack; and, at zero angle of attack, the drag of the plane would be zero.

But in a practical case, the plate or wing that is used must possess an edge of definite thickness, and this with some skin friction (undoubtedly small) gives a certain drag, even to a horizontal plate. The resultant force F , shown by the solid line in Fig. 4, is, therefore, not perpendicular to the surface but is a little back of the perpendicular, — which is shown by the dotted line. Its direction and magnitude can be determined by laying off the two components L and D , the resultant force being $F = \sqrt{L^2 + D^2}$.

Center of pressure. — When the plane is perpendicular to the air-stream, i.e., when the angle of attack is 90° , the center of air pressure, **C. P.**, on the plane is at the center of the plane. When

at 30° as at 15° . The angle of attack at which the maximum occurs, and its value are different for different aspect ratios; but the curves are all of the type here shown.

the plane is oblique, the center of pressure is found to be in advance of the center of the plane, moving more and more forward toward the entering edge as the angle of attack decreases. The position of the center of pressure for different angles of attack is shown by the curve in Fig. 8. The position is somewhat different for different

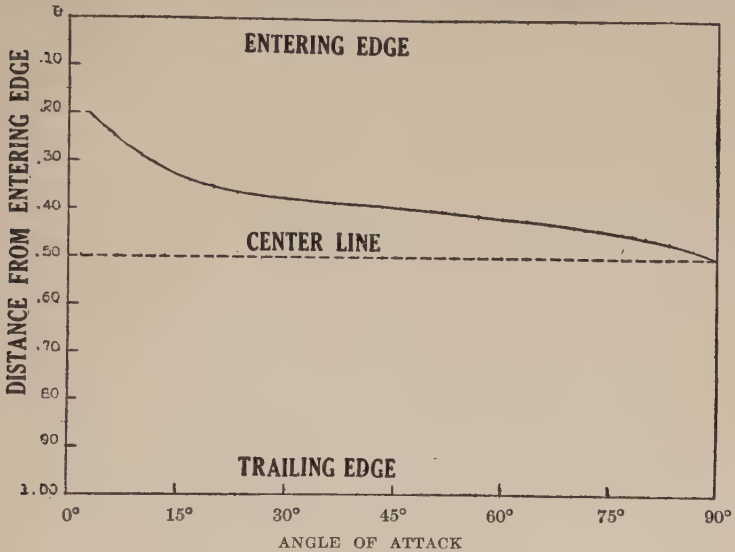


FIG. 8. Position of center of pressure on a flat plane, with aspect ratio 6, for different angles of attack.

aspect ratios, but in all cases with a flat plane the center of pressure moves forward from the center of the plane as the angle of attack decreases, thus becoming nearer to the front edge of the plane — which is called the entering edge or leading edge — and further from the rear or trailing edge.

CAMBERED WING

Decreased turbulence when cambered wing is used. — A flat plane encountering an air-stream disrupts the air, the entering edge, and to a lesser extent the trailing edge tending to produce

air eddies. The turbulence produced by such a plane has been shown in Fig. 5, which as already explained *indicates* the phenomenon but should not be understood to be an accurate representation of it. It would seem that this turbulence would increase the wing-drag and that it might decrease the lift; or, put another way, it would seem that, if the turbulence could be eliminated or reduced by any means — for example by giving the wing more or less of a stream-line form, — an increase in lift and decrease in wing-drag might be obtained. This indeed is the case, such a result being obtained by arching the wing from front to back. A wing thus arched is called a **cambered wing** and on account of its better performance is always used in airplane construction.

The flow of air past a cambered wing is shown in Fig. 9, and Fig. 13a, which again is merely illustrative and is not exact in detail.

The actual flow of air around a cambered wing may be determined by mounting a model wing in an air tunnel and discharging smoke into the tunnel ahead of the wing, or by kinematographic studies.⁷ It will be seen that the air-stream separates smoothly at the leading edge, passes over and under the wing, and rejoins smoothly at the trailing edge, if the wing is at ordinary angles of attack. Fig. 13a shows how the flow varies for different angles of attack. Flow as described above, without turbulence at either the leading or the trailing edge, is called “stream-line” flow. The lines indicating the direction of flow are called stream-lines. In like manner, a body producing approximately stream-line flow is said to be stream-line in form. It is to be noticed that this means that the large end of the object is the leading edge, the trailing edge tapering off at such a rate as to produce a minimum of turbulence and eddying. Thus it is evident that the so-called stream-lines of the automobile, with the large end at the back and the small end at the front, are not in reality stream-lines and are not good in lessening drag on the automobile. Stream-lines are desirable in

⁷ Mechanical Engineering, March 1928, Vol. 50, No. 3, p. 217.

cambered wings as they will result in a reduction of eddying and turbulence with a consequent reduction in the drag of the wing.

Creation of lift. — It is to be borne in mind that it is the downward deflection of the air that creates the lift, it being the purpose of the designer to increase this lift and at the same time to decrease the wing-drag. Lift is obtained to a certain extent by the positive pressure on the lower surface of the wing (indicated by p in Fig. 9) but to a much greater extent by the negative pressure on the upper surface, indicated by n ; commonly, as much as *three-fourths of the of the total lift is due to this negative pressure*. It will be seen that, in a cambered wing as shown in Fig. 9, the upward trend of the upper

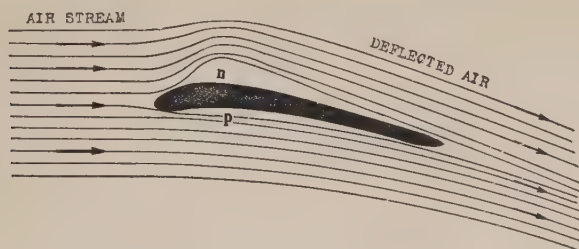


FIG. 9. Flow of air past a cambered wing; side view.

surface of the entering edge swings the air-stream upward over the wing before its final deflection downward; this leads to a decrease in pressure on the upper surface and so contributes materially to the lift. The deflection of the air downward, upon encountering the airfoil, is called downwash. The angle through which it is deflected is called the angle of downwash and is designated by ϵ , as shown in Fig. 13a.

The distribution of pressure varies along the span of the wing, the lift obtainable per square foot of wing area at the wing tip being considerably less than that obtainable per square foot nearer the fuselage of the airplane. The pressure distribution, at sections at various distances from the tip of the wing, is shown in Fig. 9a. The pressure distribution shown was determined by test on a

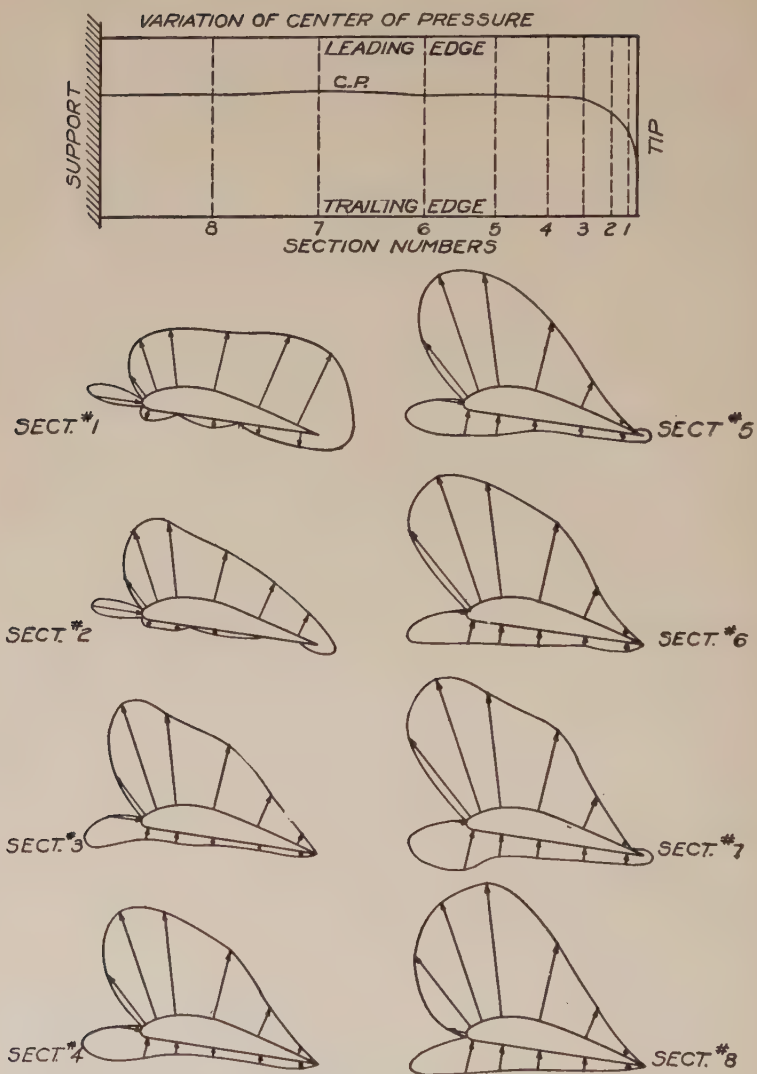


FIG. 9a. Pressure distribution and center of pressure position at various positions along the span of a cambered wing for an angle of attack of 12° .

model of a Göttingen 387-FB wing⁸ in the Langley Memorial Aeronautical Laboratory. There is flow along the span of the wing, at the wing tip, as well as air flow perpendicular to the span, with a consequent increase in the turbulence and eddying at the wing tip. This reduces the L/D ratio for that portion of the wing because of the increase in drag and the decrease in lift. It has been found that the use of end plates, that is plates perpendicular to the span with their plane in the direction of motion, reduces the amount of air flow along the span of the wing and thereby increases the lift-drag ratio and the lift coefficient.⁹

The distribution of pressure on single and multiple planes is shown in a later chapter.

It is the curvature of the upper surface of a wing that is most important, — particularly its dip toward the entering edge, often referred to as the **dipping front edge**. The curvature of the lower surface is far less important; with a well formed upper surface, a good wing can be constructed with a *perfectly flat lower* surface.

An upward turn in the lower surface toward the entering edge, corresponding to the dip in the upper surface and making what is known as “Phillips entry,” is not advantageous. The wing shown in Fig. 14, which is accurately drawn to scale, has a more effective entry than the wings sketched in Figs. 9 and 10.

Angle of attack, chord, span and area of a cambered wing. — A **wing section**, or side view, of a cambered wing is shown in Fig. 10. The **chord** of a cambered wing is a straight line, as shown, tangent to its under surface at front and rear. The **length of chord**, or more briefly the **chord**, is the length of the projection ab of the wing-section upon this line. Its symbol is c . Similarly, the **area** of a cambered wing is its area projected on a tangent plane. The **span** or **spread**, b , of a wing is the maximum distance from tip to tip. The **aspect ratio** is the ratio of span to chord, b/c . The **angle of**

⁸ National Advisory Committee for Aeronautics Technical Report No. 288, 1928.

⁹ National Advisory Committee for Aeronautics Technical Report No. 267, 1927.

attack, α , of a cambered plane is the angle between its chord and the air-stream or relative air, as shown in the same figure.

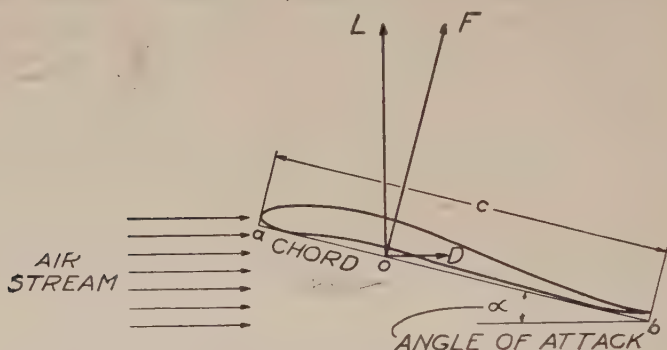


FIG. 10. Section of a cambered wing, showing angle of attack between the chord and the air-stream, and the components of force.

Wing structure. — The whole wing structure is often referred to as an **airfoil**. Wings are made in many ways; although no standard construction can be shown, the one shown in Fig. 10a is fairly typical. Each wing is commonly built up of two **spars**, as there shown, running from one end of the wing to the other. Spars may be of I-beam section, double I-beam, box construction, etc. Supported by these spars are the **ribs**, extending fore and aft, each rib having the exact shape of a wing-section. The top and bottom of each rib are commonly made of strips of spruce, held in place and strengthened by a thin web, which gives the rib an I-beam cross-section. The web is partly cut away for lightness, as shown in the figure.

The **camber** of either surface of a wing is the greatest distance between the chord and that surface, and is usually expressed as a fraction of the chord. **Upper camber** and **lower camber** are the cambers of the upper and lower surfaces of the airfoil, respectively. The camber of the bottom surface indicated in Fig. 10a is about $1/40$. **Mean camber** is the mean between the **upper camber** and the **lower camber**.

Components of force. — The force F is considered as having its point of application at the point O where it intersects the chord ab ,

as shown in Fig. 10. This point is called the **center of wing pressure, C.P.**, and is located (unless the angle of attack is very small or negative, see Fig. 13) a little in advance of the middle point of the chord, about one-third back from the leading edge.

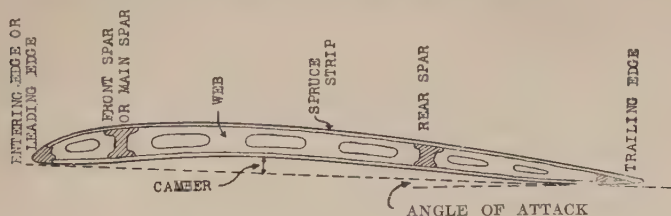


FIG. 10a. Wing structure.

The force F is more or less perpendicular ¹⁰ to the chord. The force F is resolved into its two components, lift L and wing-drag D , which also have their point of application at the center of pressure O . The direction of F can be determined by laying off L and D where these are known; $F = \sqrt{L^2 + D^2}$. In ordinary flight, D is so small compared with L , as shown in Fig. 11, that F and L are practically equal, the difference being less than one per cent.

Variation of lift and wing-drag with angle of attack of a cambered wing. — Each different airfoil-section will have its own characteristic curves for lift and drag, but all such curves have the same general trend. Fig. 11 shows curves for the coefficient of lift K_L , and the coefficient of wing-drag K_D , for a representative cambered wing, designated as U. S. A. 5 and shown in Fig. 14. These curves are typical and will serve to illustrate certain general features that are characteristic of practically all cambered wings.

¹⁰ For a certain angle of attack (when cotangent $\alpha = L/D$), F coincides exactly with the perpendicular to the chord. For a smaller angle of attack F is *back* of the perpendicular, due to the relatively large value of D compared with L . For a larger angle of attack, F is in *advance* of the perpendicular, due to the relatively larger value of L .

The ratio of the distance of the center of pressure from the leading edge to the chord length is called the **center of pressure coefficient**. Its symbol is C_P .

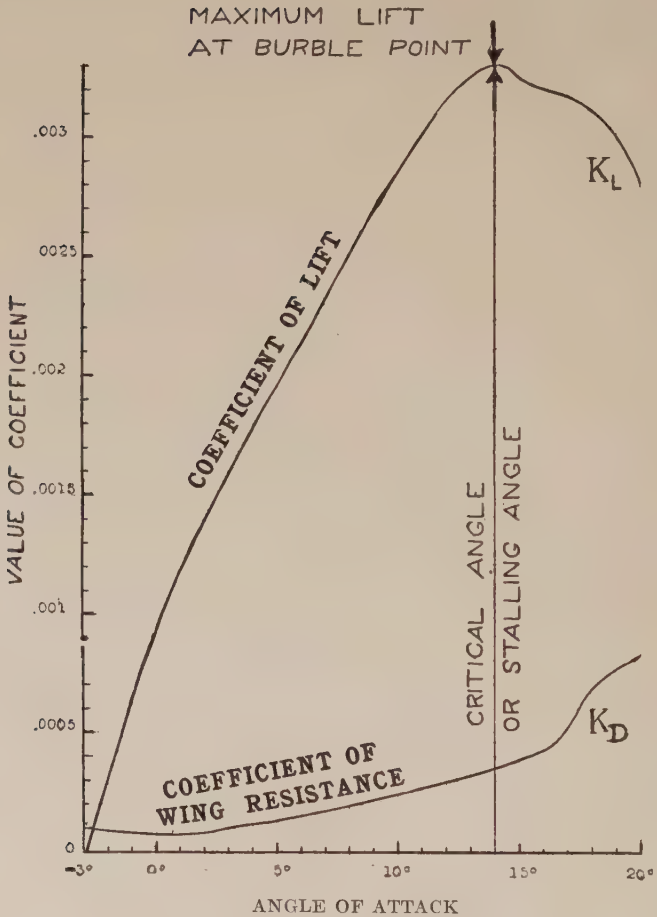


FIG. 11.¹¹ Coefficients of lift and wing-resistance or drag for cambered wing, U. S. A. 5. Lift (in pounds) = $K_L S V^2$; wing-drag (in pounds) = $K_D S V^2$, where S is in sq. ft. and V is in miles per hour. For wing-section, see Fig. 14.

¹¹ In most tests the coefficient of lift varies directly as the angle of attack, nearly to the burble point.

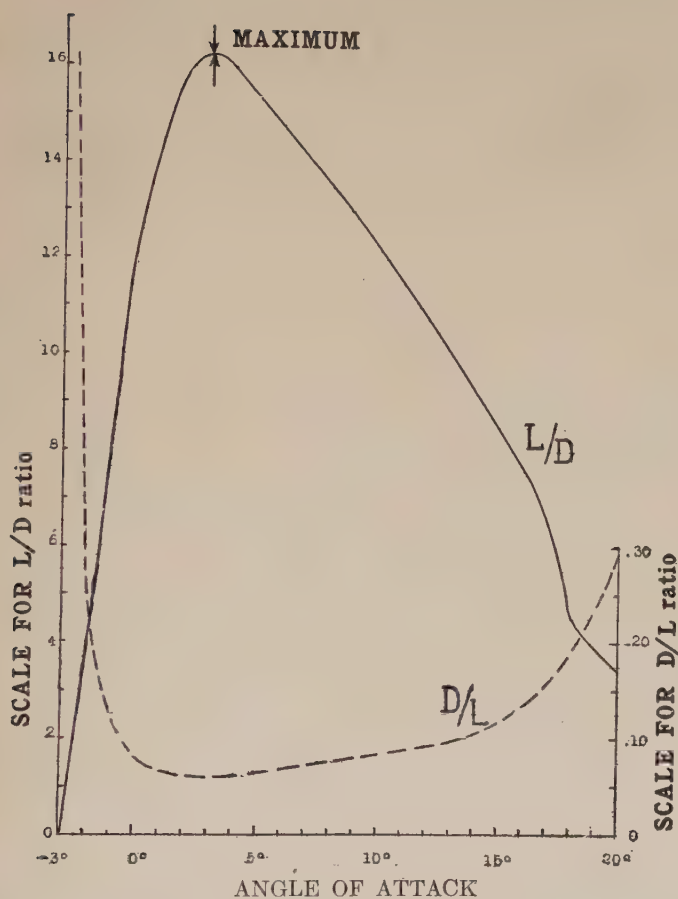


FIG. 12. Curves for L/D ratio and D/L ratio, corresponding to Fig. 11.

The curves showing the variation of K_L , K_D , L/D , and coefficient of the center of pressure with the angle of attack are called the **characteristic curves**, or the **aerodynamic characteristics**, of the airfoil.¹²

¹² The aerodynamic characteristics of most of the airfoils used in this country and in Europe may be found in National Advisory Committee for Aeronautics Technical Reports Nos. 93, 124, 182, 244, and 286.

The corresponding values for the L/D ratio (obtained by dividing K_L by K_D) are given in Fig. 12, the values for D/L being shown by the dotted curve in the same figure.

The numerical values ¹³ from which these curves are plotted are given in Table I; these values will be used in later calculations. The change in these coefficients with the density of the air is discussed in the chapter on Altitude.

TABLE I. WING U. S. A. 5

α	K_L	K_D	L/D	C_P^{14}
— 4°	— .000326	.0001500	— 2.17	
— 2°	.000346	.0000948	3.64	.753
— 1°	.000636	.0000830	7.67	.566
0°	.000910	.0000741	12.28	.498
1°	.001145	.0000803	14.28	.444
2°	.001355	.0000863	15.72	.415
2°	.001355	.0000863	15.72	.415
3°	.001565	.0000966	16.21	.377
4°	.001740	.0001092	15.98	.348
5°	.001950	.0001290	15.35	.337
8°	.002470	.0001830	13.52	.315
10°	.002870	.0002380	12.08	.303
12°	.003130	.0002890	10.84	.300
13°	.003240	.0003290	9.84	.298
14°	— .003285	.0003545	9.25	.288
15°	.003235	.0003910	8.28	.292
16°	.003205	.0004210	7.63	.298
18°	.003150	.0006900	4.57	.330
20°	.002790	.0008200	3.41	.368

Characteristic features of a cambered wing. — An inspection of the curves in Figs. 11 and 12 shows the following:

Lift with negative angle of attack. — A cambered plane exerts a lift even at a small negative angle of attack. Zero lift is usually obtained when the angle of attack is between -2° and -4° (in Fig. 11 and -3°) but in extreme cases the angle of attack may be

¹³ From tests made by Captains E. S. Gorrell and H. S. Martin, abstracted by A. Klemin and T. H. Huff; published in *Aviation*, Vol. II., p. 256, 1917. These tests were made on a model, $18'' \times 3''$, made of brass; density of standard air: 0.07608 lbs. per cu. ft.; wind velocity, 30 MPH.

¹⁴ Shown by curve in Fig. 13.

decreased to -8° or -10° before zero lift is reached. Although in most cases an airplane flies with a positive angle of attack, at high velocities it may fly with zero angle of attack or with a small negative angle of attack, — but not within two or three degrees of the point of zero lift.

In approaching the point of zero lift it is possible to go too far, so that the machine has insufficient sustentation for a horizontal flight and descends in a glide.

Lift is a maximum at about 14° . — As the angle of attack is increased, the lift increases rather uniformly, K_L reaching a maximum of more than 0.003 at an angle of attack of 14° or so, according to the particular wing. The angle of attack at which K_L is a maximum, usually between 12° and 18° , is called the **critical angle**. Beyond this maximum, which is also known as the **burble point**, the lift decreases somewhat irregularly and again becomes zero at an angle of attack of about 90° .

Up to the burble point, i.e., for an angle of attack of less than 14° or so, the air-flow past the wing is to a certain extent smooth and without eddies, as shown in Fig. 9. Beyond this point, i.e., for an angle of attack of 14° to 90° , there is a confusion of eddies and a turbulence (such as was illustrated in Figs. 3 and 5), accompanied by a decrease in lift and an increase in wing-drag. ("Burble" means "confuse"; hence the term "burble point.")

Usual range of angle of attack is about 0° to 10° . — It is seen that the lift increases more or less uniformly with angle of attack, from zero lift at -3° to maximum lift at $+14^\circ$. (It is to be understood that other wing-sections would give slightly different values.) The range for practical flight must be within these limits, without either limit being reached.

The lower limit or zero lift cannot be reached, inasmuch as some lift is necessary for sustentation; it may be approached to a certain extent at high velocities, but too near an approach will cause the machine to glide as already mentioned.

The upper limit or maximum lift is possible but in ordinary flying it, too, is only approached, for as it is approached there is

danger of a stall due to increase of wing-drag, leading to a fall or tail slide. With the decreased velocity which accompanies increased angle of attack, the stability of the machine becomes less and may vanish entirely; as the power of control depends upon velocity, the recovery of equilibrium when once lost at low speed is difficult. *Too great an angle of attack is a frequent cause of accident.* Use of the slotted wing, described later, eliminates this danger to a large extent.

Exact limits ¹⁵ cannot well be set; but, roughly speaking, the range of angle of attack is between 0° and 10° , limits which are never greatly exceeded in ordinary flight.

(The angle of attack may be increased beyond this limit — possibly up to the point of maximum lift ¹⁶ — as a machine reaches the “ceiling,” which is the highest possible altitude a particular machine can attain; also, when slowing down to minimum speed just prior to landing.)

A flat maximum in the lift curve is very desirable, being less dangerous than a sharp maximum in which the lift decreases rapidly after the critical angle is reached. A flat maximum is more readily obtained in a biplane or triplane — particularly if the planes are staggered — than in a monoplane for the maximum points for the separate planes may not coincide, so that when the separate lifts are added together to get the total lift the maximum point is broadened out.

Wing-drag is small through usual range of angle of attack; then increases rapidly. — Wing-drag, as already mentioned, is in no case zero. It is small throughout the useful range of angle of attack

¹⁵ The question of *power* is taken up later. There is, for each machine, a certain angle of attack — well within these limits — at which the power required is a minimum. If the angle of attack is either increased or decreased, there is a *very great increase* in the amount of power required.

¹⁶ Although the main wing-surfaces may thus in some cases be at their maximum lift, the surfaces used for lateral control, called **aileron**s, discussed later, should always be well below maximum lift. Otherwise they would become inoperative, for lateral control depends upon increasing the lift on one aileron and decreasing the lift on the other; if the ailerons were at maximum lift, any change would decrease the lift on both and would not give the desired control.

gradually increasing throughout this range as the angle of attack increases. As the angle of attack is further increased, the wing-drag increases a little more rapidly until the burble point or point of maximum lift is reached; after which the wing-drag increases very rapidly, — finally reaching a value of 0.003 (more or less) at an angle of attack of 90° .

L/D ratio has a maximum value of about 16 in middle range of angle of attack. — If the wing-drag were constant, the L/D ratio would be a maximum when the lift is a maximum. On account of the increase in wing-drag with angle of attack, the L/D ratio reaches a well defined maximum before the maximum lift is reached, usually at an angle of attack between 3° and 8° . In Fig. 12, this maximum of 16.2 occurs at $+3^\circ$. This is a good value for L/D . Values as high as 24 have been obtained with some wing-sections,¹⁷ — at a sacrifice perhaps of some other feature, such as stability or ease of construction.

Comparison with flat plane. — By comparing the curves in Figs. 11 and 12 for a cambered wing, with those of Figs. 6 and 7 for a flat plane, it is seen that the cambered plane gives more lift (the maximum value being about 50 per cent. more), gives less wing-drag and a much greater L/D ratio, — nearly three times as great. For these reasons a cambered wing is always used.

Shifting of center of wing pressure with angle of attack. — The position of the center of pressure for the cambered wing in question, U. S. A. 5, is shown in Fig. 13. *All cambered wings show a marked shifting of the center of pressure toward the rear of the plane, when the angle of attack is small and is decreasing; — a bad feature for stability as discussed in a later chapter.*

In this one respect a cambered wing is inferior to a flat plane, in which the center of pressure moves forward when the angle of attack is decreasing, as shown in Fig. 8.

The shifting of the center of pressure shown in Fig. 13 is much

¹⁷ National Advisory Committee for Aeronautics Technical Reports Nos. 93, 124, 182, 244, and 286.

less than is found in the case of many wings, the section of wing here used being in this respect satisfactory.

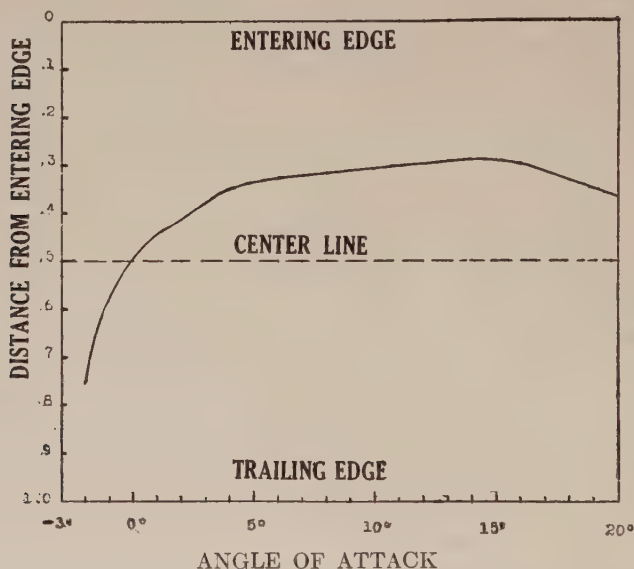


FIG. 13. Position of center of pressure on a cambered wing (U. S. A. 5.) with aspect ratio 6, for different angles of attack.

Variation of pressure distribution on an airfoil with angle of attack, as shown by wind tunnel tests.¹⁸ — Tests made by Montgomery Knight and Oscar Loeser, Jr., at the Langley Memorial Aeronautical Laboratory, on a Göttingen 387-FB wing model show the pressure distribution on the surface of an airfoil to vary with the angle of attack as shown in Fig. 13a.

The vertical component of the summation of the pressures over the wing surface is the force available as lift. The horizontal component of the same summation of pressures is the force called wing-drag. A comparison of the diagrams for the different angles of attack shows that as the angle of attack increases to large values

¹⁸ National Advisory Committee for Aeronautics Technical Report No. 288, 1928.

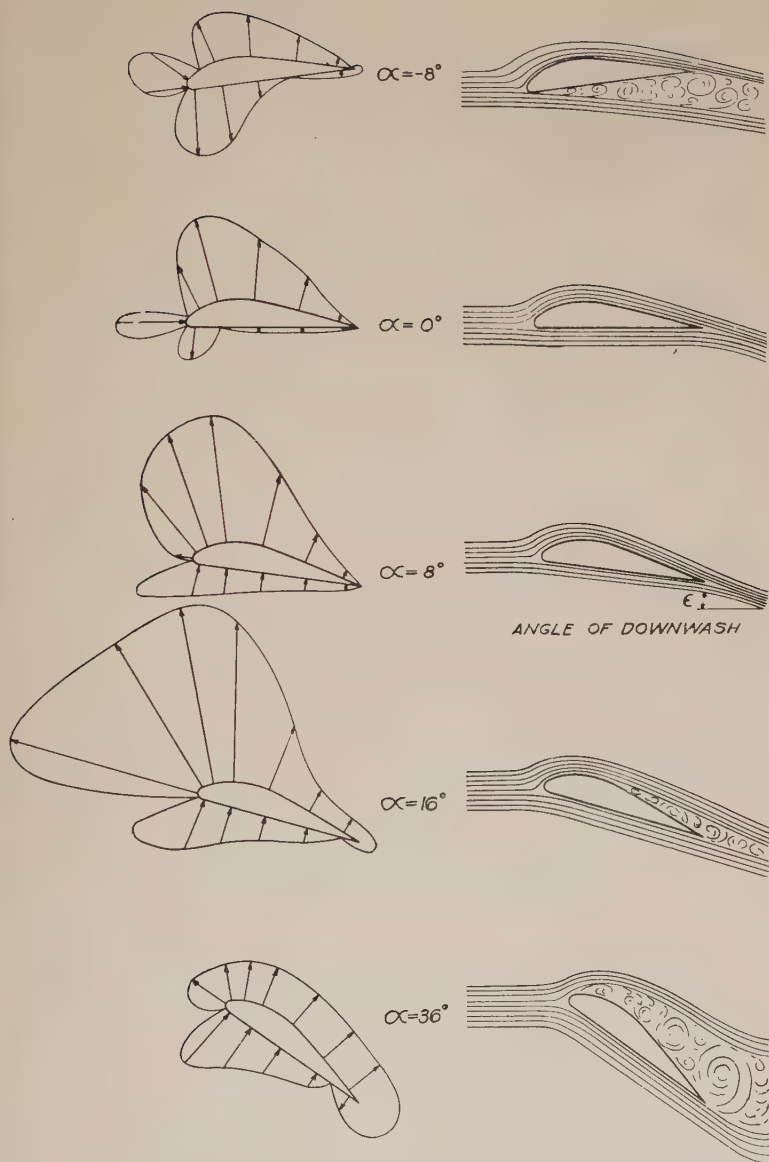


FIG. 13a. Distribution of pressure on a cambered wing at different angles of attack. Sketches to the right show, approximately, the manner of air-flow at the different angles of attack.

(over 14° to 15°), the vertical component of the summation of pressures becomes small and the horizontal component becomes large, with a consequent reduction in both the lift and the lift-drag ratio. The -8° angle of attack for this wing-section was the approximate position for zero lift. The angle of an airfoil when its lift is zero is called the **angle of zero lift**. It varies with the airfoil shape.

Tests were made to determine the flow of the air around an airfoil at different angles of attack in an effort to explain the reason for the decrease of the negative pressure on the upper side of the airfoil at high angles of attack. These tests indicate a flow of the kind shown at the right in Fig. 13a. For the negative angle of attack shown, the air is deflected up, away from the part of the upper surface toward the leading edge. This causes a region of rarefied air in which there is a negative pressure on the surface. The air, being deflected downward, away from the portion of the lower surface toward the leading edge, is rarefied in this region also, with a consequent negative pressure over this part of the surface.

With moderate angles of attack, the air has stream-line flow about the airfoil. However, when a certain angle of attack, called the critical angle, is reached, the air breaks away from the upper surface causing turbulence and eddying above the upper surface,¹⁹ much as is shown in Fig. 5. This greatly reduces the negative pressure obtainable on the upper surface and at the same time increases the drag. The greater amount of lower airfoil surface exposed to the air-stream also increases the amount of drag at large angles of attack.

The use of the Handley-Page slot on any wing greatly increases the critical angle of the wing. A description of the slotted wing and its action will be found in the next chapter under the discussion of stalling of an airplane.

Wing-section. — There is no one type of wing that is best. The particular wing to which all the curves here given refer is shown in

¹⁹ Mechanical Engineering, March 1928, Vol. 50, No. 3, p. 217.

Fig. 14 and is fairly representative. But it will be understood that in different machines different wings may best be used, according



FIG. 14. Section of wing, U. S. A. 5.

to the particular features to be emphasized; high speed in one, large load-carrying capacity in another; stability in one, quickness in manœuvring in another, and so forth.

The characteristics of any particular wing-section are shown by means of curves, such as those shown in Figs. 11, 12 and 13. The usefulness of these curves in determining the problems of flight will be brought out in the following chapters.

Comments on wing-sections. — A few comments on wing-sections may here be made, although the reader may find it well to postpone their perusal until he has read some of the subsequent chapters describing various relations and characteristics of an airplane in flight. Mechanical as well as aerodynamic considerations have to be kept in mind by the designer; there must be room for spars and ribs of adequate strength.

For climbing and for heavy lift, a wing with deep camber (particularly on the upper surface) and large value of K_L should be used. For this purpose a deeply cambered wing is flown at low speed, and at a large angle of attack as shown in Fig. 15. Such a wing, however, is utterly unsuited for flying at high speed and small angle of attack, as shown in Fig. 16, on account of its great drag at small angles of attack.

For speed, the wing should be flatter with only a little camber, with less lift and with the least possible wing-drag at small angle of attack and high velocity. It is necessary to sacrifice either speed or lift. A speed wing is sketched in Fig. 17.

Again, both speed and lift may be sacrificed for stability. As has been shown, the center of pressure on a cambered wing, convex upward, shifts with change of angle of attack (when the

angle of attack is small) in the *wrong direction* for stability. If a cambered wing were concave downward — a very bad wing for lift — this shifting of the center of pressure would be in the *right direction* for stability. The two effects may be combined, in varying proportions, by giving a wing a **double curvature**, as shown in Fig. 18. In this case, when the machine starts to dive the air strikes, or tends to strike, the reversed curve near the rear of the wing and restores equilibrium; but this means less lift and more drag.

The characteristics of an airfoil, although in a general way shown by its section, are best shown by curves for its performance, as in Figs. 11, 12 and 13.

A high maximum to the K_L curve is of no advantage in a high speed machine nor in ordinary flight; it gives, however, the ability to climb to high altitudes and gives a low landing speed, as brought out in the next chapter.

The L/D curve should show a good value, not necessarily a maximum, at about the angle of attack for which the machine is to be flown; thus, in a high speed machine, it is desirable to have a large value for L/D at a very small angle of attack. This is only another way of saying that wing-drag D should be small.



FIG. 15. Wing with high camber, suitable for large lift and slow speed, when flown at large angles of attack as shown.



FIG. 16. Same wing at small angle of attack, entirely unsuitable for high speed on account of large wing-drag due to its camber.



FIG. 17. Flat, stream-lined wing with little camber and small lift; suitable for high speed on account of its small wing-drag.



FIG. 18. Wing with reversed curvature toward trailing edge for increased stability. This is paid for by an increase in wing-drag and a decrease in lift.

In a high speed machine, which is to be flown at small angle of attack and at small K_L , it is desirable to have a curve for K_L that is not too steep as it approaches zero lift; thus, it is desirable to

obtain a certain lift, when the plane, let us say, is 3° or 4° rather than 1° or 2° from the angle of attack of zero lift. There is then less loss of sustentation, when the machine dips a little as it oscillates about its normal direction of flight.

NOTE. The development of the subject in the chapters immediately following depends so directly upon Chapter I, that the general description of the airplane, its structure and control, is deferred until a subsequent chapter on Single and Multiple Planes. This description may, however, be read at this point to advantage.

Lift, drag, velocity and power are all directly affected by the density of the air. A discussion of this is also deferred; see a later chapter on Altitude.

CHAPTER II

RELATIONS IN HORIZONTAL FLIGHT

The relation between lift, wing area, and airplane velocity, as derived in the preceding chapter, furnish a basis for determining some interesting relations in horizontal flight. The effect of wing-drag will be deferred until Chapter III, the present chapter dealing only with the lift equation, and the relations between velocity and angle of attack which may be derived from it.

In horizontal flight, $\text{weight} = \text{lift} = K_L S V^2$. — We have seen that the lift that supports an airplane is equal to the product of the area of wing S , the square of the velocity V , and a coefficient of lift

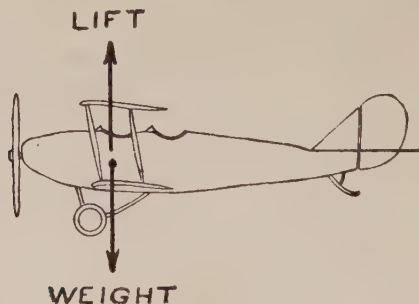


FIG. 19. Lift = weight in horizontal flight.

K_L that varies with the angle of attack:

$$\text{Lift} = L = K_L S V^2.$$

For sustentation in horizontal flight, see Fig. 19, the lift must be just equal to the weight of the machine, including its load; we, accordingly, may write

$$\text{Weight} = W = K_L S V^2.$$

Weight acts downward through the **center of gravity** or **C. G.**; lift acts upward through the **center of lift** or **C. L.** These two centers are never far apart, although they rarely coincide exactly. When the center of gravity is in front of the center of lift, there is a moment or couple tending to make the machine nose down; when the center of gravity is back of the center of lift, there is a couple tending to make the machine nose up. In neither case does the couple have any effect upon the value of weight and lift (which are equal), although it does affect longitudinal stability discussed later.

Velocity equals square root of "loading" divided by square root of K_L .—The preceding equation, when transposed, gives the important formula for velocity in horizontal flight,

$$V = \sqrt{\frac{W}{SK_L}}.$$

This formula, although simple, is quite complete and will bear careful study, for it leads to a number of interesting conclusions, the appreciation of which is essential to a proper understanding of flight.

The ratio W/S is the weight per unit area of wing and is called the **wing loading**. It is the loading, rather than weight or area, that affects the value of V . The formula shows that the velocity of an airplane depends solely upon the loading and upon K_L . Here W is the weight of the loaded machine.

The only possible way for changing the speed of a machine, or for getting different speeds in different machines, is by changing the loading or by changing the value of K_L . In practice there are of course limits to both of these changes. For a machine in level flight, in which the loading cannot be changed, the only way of changing the speed is by changing the value of K_L by a change in the angle of attack.

The loading W/S is commonly about 10 or 12 lbs. per sq. ft., being less in heavy, slow machines and being more in light, fast machines; racing machines may have loadings of more than 30

lbs. per sq. ft. The usual limits for K_L are about 0.0008 and 0.0032.

This gives us at once the speed variation, shown in Fig. 20, for any machine irrespective of wing-section or other features of design except loading. Each curve in Fig. 20 is for a different loading.

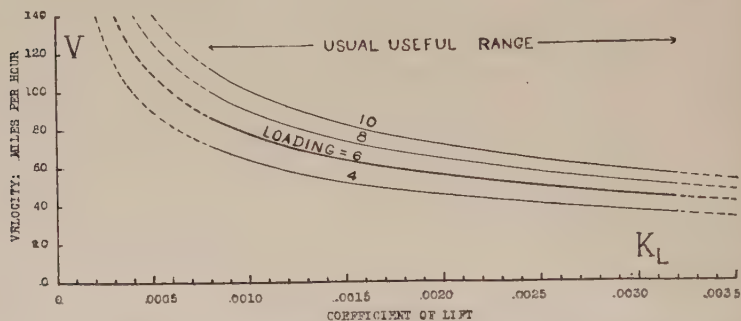


FIG. 20. Variation of velocity with coefficient of lift for any airplane, when loading is 4, 6 (heavy curve), 8 and 10.

The heavy curve shows the change of speed, with K_L , for a machine with loading $W/S = 6$, this being the plot of the equation $V = \sqrt{6 \div K_L}$. The light curves are for loadings 4, 8, and 10, an increase in loading raising the curve and thus indicating a greater velocity.

It is seen that velocity increases as K_L decreases; if K_L were zero, V would have to be infinite to create a lift equal to the weight, as is necessary for sustentation.

Speed range.—A machine that has a maximum speed of 100 miles per hour and a minimum speed of 45 miles per hour is said to have a speed range of 55 per cent. The speed range is the difference between maximum and minimum speed, divided by the maximum speed. The range in speed depends upon the range in the value of K_L .

Thus it is seen that, if we take the limits of K_L as 0.0008 and 0.0032, the **speed range** for any machine is fifty per cent. The curves in Fig. 20 are drawn solid between these limits. Commonly the speed range is somewhat less than fifty per cent., but in some

cases is a little more. (A minimum value of K_L a trifle less than 0.0008 may be attained in some instances; but a greater value, 0.0009 or more, is perhaps a more usual minimum.)

By way of illustration, with limits 0.0008 and 0.0032 for K_L , a machine with loading $W/S = 10$ would have speed limits as follows, the speed range being 50 per cent.;

$$\text{Maximum speed} = \sqrt{10 \div 0.0008} = 112 \text{ MPH.}$$

$$\text{Minimum speed} = \sqrt{10 \div 0.0032} = 56 \text{ MPH.}$$

As a further illustration, with limits 0.00074 and 0.0034 for K_L , the speed range would be about 54 per cent.; thus,

$$\text{Maximum speed} = \sqrt{10 \div 0.00074} = 116 \text{ MPH.}$$

$$\text{Minimum speed} = \sqrt{10 \div 0.0034} = 54 \text{ MPH.}$$

In this case, speed range = $(116 - 54) \div 116 = 0.54$ or 54 per cent.

A greater speed can be attained only by increasing the loading or by decreasing K_L . For example, if a speed of 200 MPH. is to be attained: W/S must equal 29.6, if $K_L = 0.00074$; W/S must equal 20, if $K_L = 0.0005$; W/S must equal 10, if $K_L = 0.00025$; etc.

The advantage of a large speed range ¹ — not only a high maximum speed for flying but also a low minimum speed for landing — is obvious. To get a sufficiently low landing speed the designer must choose a small loading if he cannot choose his wing section; see Fig. 20.

However, if he is free to choose the wing section to be used he can choose one that will permit the required maximum or top speed, and that will also have a high maximum value for the lift coefficient.

¹ Some early machines had a very small speed range, let us say from a minimum of 35 to maximum of 50 miles per hour, giving a speed range of 15 miles per hour. A gust from behind of more than 15 miles per hour would reduce the relative air speed below the requisite 35 miles per hour necessary for sustentation, so that the machine had no support. This was one cause for the so-called *holes in the air*.

Maximum value of lift coefficient, K_L , determines landing and stalling speeds. — At landing, as in stalling, the speed of the airplane is reduced by increasing the angle of attack to the critical angle, thus increasing the drag. The lift is a maximum for this angle. The landing speed or the stalling speed of the airplane can therefore be computed by the following equation, if the loading and the aerodynamic characteristics of the airfoil used are known.

$$\text{Landing and stalling speed} = \sqrt{\frac{W}{SK_{L \max}}}.$$

Ground effect. — The landing speed of the airplane may be slightly lower than the speed as computed by the above equation on account of K_L increasing slightly as the airplane nears the ground. This increase in the lift coefficient as the airplane approaches the ground is known as **ground effect**. It seems to be caused by the layer of air trapped between the wing and the ground being able to give a larger lifting reaction on the wing than when the wing is far enough above the ground so that the supporting effect of the ground is absent.

Tests on a Vought VE-7 airplane ² show that the lift-drag ratio is increased from 9 to about 12.5 on approaching the ground, the same angle of attack being kept in both instances. This was caused by the combined effect of an increase in lift and a decrease in drag, the decrease in drag being the more noticeable of the two.

A given machine has a definite velocity for each angle of attack, and this is controlled by the elevator. — Since K_L has a different value for each angle of attack, it is seen that the velocity of a machine varies with angle of attack and, for a given loading, *velocity depends only* ³ *upon angle of attack*. The angle of attack is controlled by the pilot by means of the elevator, as discussed later in Chapters X and XI.

² National Advisory Committee for Aeronautics Technical Report No. 265, 1927.

³ The density of the air is here assumed to be uniform; see a later chapter on change of density and K_L with altitude.

The variation of K_L with angle of attack, for a particular wing-section, is shown in Fig. 21, reproduced from Fig. 11 of the preceding chapter. The numerical values from which the curve is plotted are given in Table I, page 21.

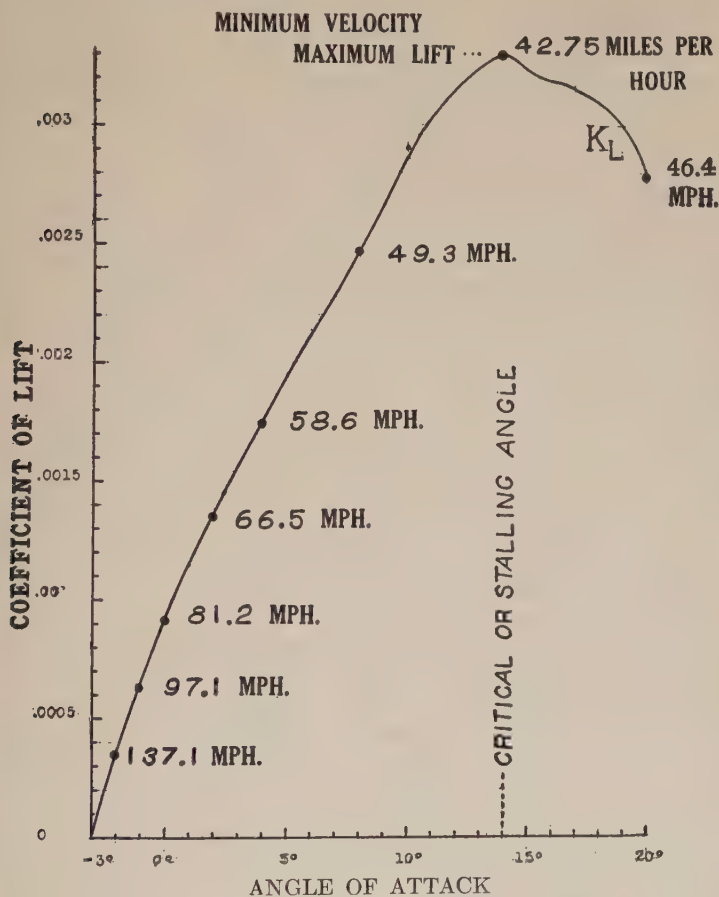


FIG. 21. Variation of coefficient of lift with angle of attack, for a particular wing-section; aspect ratio 6. Velocities are marked for several points, assuming a loading of 6 lbs. per sq. ft.

For any given loading, the value of V corresponding to any point on this curve is readily determined. For example, suppose

$W/S = 6$. For an angle of attack of 4° , from the curve or table, $K_L = 0.00174$; hence, $V = \sqrt{6 \div 0.00174} = 58.6$ miles per hour. The values of V , determined in this way, are marked for several points on the curve. It is seen that for each angle of attack, the velocity has one definite value.⁴

Minimum velocity occurs at the point of maximum K_L , namely at the critical angle of attack or burble point. — It is seen that the minimum velocity occurs when the value of K_L is a maximum, namely at the critical angle of attack or burble point. For any other angle of attack, K_L is less and V is correspondingly greater; in other words, when the angle of attack is either greater or less than the critical angle, *a greater velocity is required in order to produce the lift equal to the weight*, the condition necessary for horizontal flight.

⁴ *Modification in complete machine.* — The lift curve for a wing is modified in a complete machine by whatever lift there is (either positive or negative) on other parts of the machine — body, tail and other surfaces — and, in a biplane or triplane, by an interference between the planes that reduces the lift. This reduction is less when the gap between the planes is large and when they are given considerable stagger than when the gap is small and there is no stagger. Lift likewise increases with aspect ratio, the ratio of wing-span to chord. For the curves here shown the aspect ratio is assumed to be 6, the usual standard value.

For simplicity a detailed consideration is not given here of these features, for they in no way affect the general character of the conclusions, although they do affect the precise numerical values. Proper corrections have to be applied when exact numerical values are to be obtained.

The net result of these corrections usually shifts each point on the lift curve a little to the right, say a degree or so, so that a lift $K_L = 0.00174$ and velocity 58.6 MPH. shown by the curve at 4° would, for a complete machine, be at say 5° , and so on for other points, the shift being slightly different for different points. So far as lift and velocity are concerned, the effect of these corrections is merely to change the angle of attack at which a particular value of lift and of velocity occur. Put in a different way, at small angles (perhaps through the working range) the lift curve is somewhat lowered and at large angles is somewhat raised, — for at large angles the lift of the airplane fuselage becomes effective.

The lift curve for a complete machine may be determined by applying proper corrections to the lift curve of the wing (which is of course the chief factor) when data for these corrections is available; but it is best determined by a wind-tunnel test with a complete model. Some of these corrections are to be considered later in the chapter on Single and Multiple Planes.

Variation of velocity with angle of attack. — The variation of velocity with angle of attack is well shown by the curves in Fig. 22, which correspond to Fig. 21 and refer, therefore, to a particular wing-section, — not to any wing-section as was the case in Fig. 20. Curves for the variation of velocity with angle of attack for other wing-sections would have much the same general form.

The heavy curve in Fig. 22 shows the velocity for a loading $W/S = 6$; the light curves, for loadings of 4 and 8, — the greater loading always corresponding to the higher velocity.

It is thus seen that there is a definite minimum velocity which occurs at the critical angle of attack — in this case 14° — when K_L is a maximum, as was also shown in Fig. 21. If a machine loses velocity below this minimum, it cannot sustain itself and is said to **stall**, — the critical angle of attack being also called the **stalling angle**.

The velocity increases on each side of this minimum, with change of angle of attack, so as to furnish the necessary sustentation, and would have to be infinite were K_L equal to zero, namely if the angle of attack were decreased (in this case) to -3° or were increased

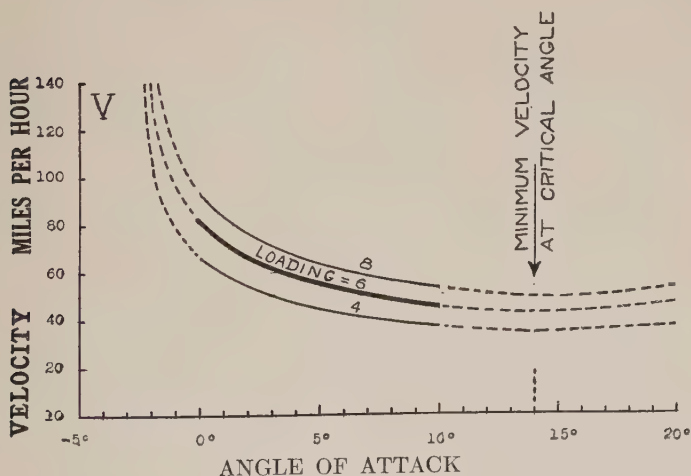


FIG. 22. Variation of velocity with angle of attack for particular wing-section, when loading is 4, 6 (heavy curve) and 8 lbs. per sq. ft. These curves correspond to the curve in Fig. 21.

to about 90° ; but, as already pointed out, there are limits to the working range of angle of attack and velocity.

Usual working range. — Between the limits of 0° and 10° (corresponding to $K_L = 0.00091$ and $K_L = 0.00287$) the curves are drawn as solid lines; these limits would become $-1/3^\circ$ and 12° , if the limits of K_L were taken as 0.0008 and 0.0032 as before. (It is understood that *precise* limits cannot be set.) This shows the usual working range: two or three degrees less angle of attack would cause a *glide*; two or three degrees more angle of attack would cause a *stall*. An *inclinometer* is commonly used to indicate (usually by a bubble) the inclination of the machine with the horizontal but should not be depended upon. A *stall indicator* is less frequently used to display a danger signal when the *stalling angle* is approached.

Possibility of changeable wing-area or camber. — For structural reasons, wings are made with fixed area and camber. A practical wing with either of these adjustable would do much to advance the art of flying, for it would make possible a great increase in speed range, both by increasing the maximum and decreasing the minimum speed. These improvements have long been considered, the adjustable camber now seeming the more promising of the two.

With adjustable wing-area, the pilot would use large area for low speed and would use small area for high speed.

With adjustable camber, the pilot would use for low speed such camber as gave maximum lift. For high speed he would flatten out the wing and so get less lift without a reduction in angle of attack. This flattening of the wing would also bring a reduction of wing-drag, — a highly important advantage at high speeds.

Use of flaps on wings. — Considerable experimental work has been done with airfoils having flaps on the leading or trailing edge, or on both edges of the airfoil, these flaps being movable, making it possible to change the curvature of the upper and lower surfaces of the wing while in flight. A cross-section of such a wing is shown in Fig. 22a.

It will be remembered, from Chapter I, that an increase in the camber of an airfoil increases the lift and drag coefficients. With the wing shown in Fig. 22a, the lift coefficient may be increased



FIG. 22a. Airfoil with flaps on leading and trailing edges, for varying shape and characteristics of the airfoil while in flight.

FIG. 22b. A plain and a slotted airfoil.

by turning down the flaps, as shown by the dotted lines, increasing the camber by an amount x . There will be a decrease in speed if the flaps are down, because the drag on the wing is then increased. This increase in drag is an advantage when landing, as it permits a steep glide angle without too much increase in speed. For normal flying, the flaps would be as shown by the full lines in Fig. 22a. The airfoil would then be identical in action with the same type of airfoil without flaps, except for a slight increase in the drag coefficient caused by the break in the upper and lower surfaces of the airfoil where the flaps meet the main airfoil surfaces. This increase in drag reduces the top speed of the airplane slightly.

There are several important disadvantages in using wings with flaps. The center of pressure changes when the flaps are pulled down, thus changing the balance of the airplane and making it more difficult to control. Pulling down the flaps also causes more turbulent flow of air from the trailing edge of the wing. This turbulent flow of air from the trailing edge of the wing does not give as effective control by the tail surfaces of the plane, as when the flow is smooth and without eddies. The weight of the operating mechanism of the flaps reduces the pay load that may be carried by a given plane. The control of the plane is made more complicated, as the flaps are manually operated.

The Handley-Page slotted wing. — In 1920, Mr. Handley-Page, of England, discovered that an airfoil mounted on the front of the regular airfoil, with provision for moving the auxiliary airfoil away from the regular airfoil surface, thereby making a slot between the two airfoils, was very effective in increasing the lifting power of the airfoil when operated at large angles of attack. He found that at angles of attack at which the airplane would normally stall, because of the falling off of the lift coefficient, the lift coefficient of the slotted wing would still be increasing.

The arrangement of the auxiliary airfoil is somewhat as shown in Fig. 22b.

For normal flying the slot is closed, the auxiliary airfoil being against the front of the main airfoil. With the slot closed, the airfoil characteristics are the same as for the plain airfoil of the same contour, except for a slight increase in drag, caused by the break in the surface of the airfoil where the auxiliary and main airfoils meet. The increase in drag causes a corresponding decrease in the lift-drag ratio.

The opening of the slot affords a passage for the air to flow from the region of high pressure, under the wing, to the region of negative pressure, on the upper surface of the wing. The passage formed between the airfoils is of such shape as to direct the flow of air backward along the upper surface of the main airfoil. This maintains the flow of air over the upper surface of the main airfoil at greater angles of attack than the normal critical angle for unslotted airfoils.

It is evident then that the slotted wing is of advantage only at large angles of attack, where the lift coefficient ordinarily decreases sharply. The slotted wing permits operation of the airplane at larger angles of attack, without stalling, thus reducing that hazard. It also makes it possible to take-off at a lower speed and at steeper angles than heretofore. The reduction in speed at landing and at taking-off is evident if it is remembered that the maximum lift coefficient of the slotted wing is much higher than that of the unslotted wing, the minimum speed at which the airplane can be operated depending on this maximum value.

The disadvantages of the slotted wing are similar to those for the wing with flaps. The increased drag of the broken airfoil surfaces reduces the top speed of the plane. The weight of the control mechanism for the slot reduces the pay load of the airplane. The larger angles of attack possible with the slotted wing necessitates longer landing gear, to prevent the tail skid striking the ground too long before the wheels.

The original Handley-Page slot was connected with the aileron, both being operated by the control stick. The action of the slot has since been made automatic, by mounting the auxiliary airfoil in such a manner that the slot opens as the angle of attack reaches 12° .

In a test of a Navy airplane equipped with slotted wings, a take-off at an angle of approximately 45° was made after a run of only 50 feet on the level. This is much better than any performance heretofore accomplished with ordinary wings.⁵

Power has no direct effect upon velocity. — It has been shown that the velocity of a machine depends directly upon angle of attack (ignoring the possibility of a change in wing-area or camber and the effect of altitude), angle of attack being controlled by the position of the elevator. It may well be asked: What about power? What effect upon velocity has the amount of power supplied by the engine? The answer is: The power supplied by the engine has no *direct* effect upon velocity; for velocity is directly controlled by the elevator. Power has a direct effect upon the inclination of the flight path. The effect of power is shown in the following paragraphs.

Let us suppose, for example, a machine is flying with a certain angle of attack — say, 4° — controlled by the position of the elevator. The velocity of flight is then definite, — 58.6 MPH., if we use data in Fig. 21. At a definite velocity and angle of attack, the drag of the airplane (structure as well as wings) is definite — in a certain instance 263 lbs. — to overcome which there must be an

⁵ National Advisory Committee for Aeronautics Technical Report No. 249, 1927.

exactly equal thrust (263 lbs.) requiring the supply of a certain amount of power (in this instance 42 horse power). But this definite amount of power that is required may or may not be supplied by the engine, for this depends on the throttle. Let us see what happens when the engine does not supply this amount of power.

Amount of power supplied by engine determines whether machine climbs, glides or flies horizontally; but, if angle of attack is not changed, does not affect velocity. — If the engine supplies just the right amount of power required to overcome the total drag, the machine flies *horizontally*, as in Fig. 23. If it supplies more power, the machine takes an oblique path *upward*, as in Fig. 24, the “surplus power” being used *against gravity*. If the engine supplies less power than is necessary to overcome resistance, the machine takes an oblique path *downward*, as in Fig. 25, the necessary additional power being in this case *supplied by gravity*.

Thus, if the power required to overcome the drag is 42 H.P., there are the three cases: when the engine delivers ⁶ 42 H.P., flight is horizontal; when it delivers more power, 47 H.P. for example,

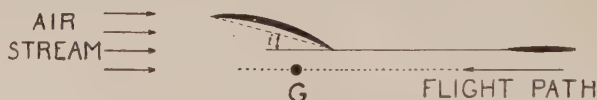


FIG. 23. Horizontal flight.

the machine climbs, automatically taking a flight path inclined upward at such an angle that the surplus 5 H.P. is used in overcoming gravity; when the engine delivers 37 H.P., the machine takes an oblique path downward at such angle that 5 H.P. is derived from gravity. The angle of attack — the angle between the chord and the relative air or flight path — being the same in the three cases, the velocity relative to the air is substantially the same

⁶ The power available for producing thrust, delivered through the propeller, is here referred to. The question of propeller efficiency is not here taken into consideration.

irrespective of whether the flight path is horizontal or slightly oblique.

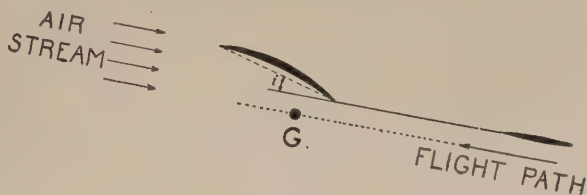


FIG. 24. Oblique flight, upward. The same angle of attack and velocity as in Fig. 23.

It is seen that if power is slightly increased or decreased, by adjustment of throttle, the inclination of the flight path is changed, but (provided the angle of attack is not changed) velocity remains unchanged. Indeed, if the power is entirely cut off, the machine takes an oblique flight path downward at a definite **gliding angle**, while the velocity at small gliding angles remains practically unchanged. These relations will be more precisely discussed in Chapter VII on Power Relations in Flight and in Chapter VIII on Climbing and Gliding.

When horizontal flight is to be maintained, velocity is changed by a simultaneous adjustment of throttle and elevator. — From the foregoing, it is seen that the one way to change velocity is to change the angle of attack by means of the elevator; furthermore, if horizontal flight is to be maintained, the throttle must be adjusted at the same time so that the amount of power required for horizontal flight is supplied by the engine, — otherwise the flight path will be oblique. The pilot does not speed up and slow down

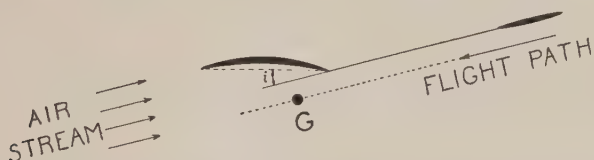


FIG. 25. Oblique flight, downward. The same angle of attack and velocity as in Figs. 23 and 24.

merely by opening and closing the throttle, as in an automobile. As a matter of fact an airplane is, in normal flight, practically a constant speed machine, flying usually at the one velocity corresponding to a certain best angle of attack, for which the machine is designed.

It takes more power to fly at low speed or at high speed than at an intermediate speed. The amount of power required to maintain horizontal flight, as shown in a later chapter, increases very rapidly when the velocity is either increased or decreased beyond a rather narrow range. Power as well as stability is, accordingly, a factor — in many cases a determining factor — in deciding the range of velocity and the limiting values for the angle of attack and for K_L .

To find out how much power is necessary for horizontal flight, we must first know the thrust required and this is determined by the total drag that is to be overcome. This will be investigated in the next chapter.

Conditions of steady flight have been assumed. — The foregoing relation between velocity and angle of attack is the relation in *steady flight*, and is modified by the inertia of the machine when velocity is changing; it is assumed, furthermore, that the flight path is not greatly inclined with the horizontal. That is, the relation is modified by the inertia of the machine when velocity is changing, and is also modified when the flight path is far from horizontal, as in a dive.

After a change of elevator or throttle, there is a brief lapse of time before steady conditions of flight along the new flight path are reached. Thus, the *immediate* effect of opening the throttle is increased speed along the original flight path. The pilot may continue at this increased speed by proper elevator control; or, as already stated, he may use part or all of the added power for climb.

Although the relation between angle of attack and velocity is direct and simple, a general relation between elevator position and angle of attack or velocity cannot be so simply stated. It is dependent upon several factors, including the setting of the hori-

zontal stabilizer, the amount of slip-stream, and the relative positions of the center of thrust and center of drag, which will be better understood after the chapter on Longitudinal Stability has been read.

Flying attitudes. — The position of a machine in horizontal flight with respect to its flight path, which is horizontal, is called its attitude. In all machines, as usually ⁷ constructed, the wings are rigidly fixed to the airplane body. The angle of attack between the wings and the relative air can, therefore, be changed only by changing the attitude of the whole machine. This the pilot accomplishes by means of the elevator.

There are three attitudes in flight. First, there is the normal attitude, in which the airplane flies with “even keel”; the airplane body lies in the line of the flight path and offers least resistance. This attitude gives a certain normal angle of attack between the wing-chord and relative air. Second, there is the “tail-low” attitude, giving a larger angle of attack; and, thirdly, the “tail-high” attitude, giving a smaller angle of attack.

In the tail-low attitude, the air pressure on the body adds to the lift; in the tail-high attitude, it subtracts from it.

A very decided tail-high or tail-low attitude should be avoided by proper balancing. The setting of the horizontal stabilizer is commonly made adjustable for this purpose.

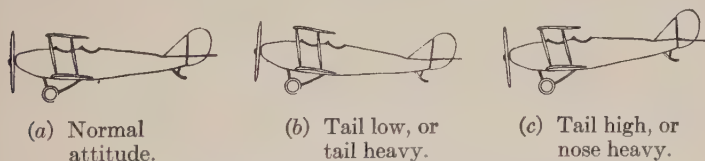


FIG. 25a. Three attitudes in horizontal flight.

⁷ An adjustable wing would permit a change of angle of attack without a change of attitude. An airplane so equipped could fly, under changing conditions, with even keel; the thrust could be maintained in a constant direction with respect to the flight path. The objections to an adjustable wing are structural. For a description of a machine so constructed see Chapter XVI.

CHAPTER III

DRAG

In Chapter I, we saw that when a body was moved rapidly through the air a force was exerted on the body by the air, one component of this force always being in the direction of the air-stream and opposing the motion of the body. When a whole airplane is moved through the air, a similar impeding force is experienced. This impeding force is called the **drag** or **resistance** of the airplane. These two words will be used interchangeably in the following discussion and diagrams.

Drag must be overcome by propeller **thrust**, which is a force in the direction of flight, or nearly so.¹ This is shown in Fig. 26.



FIG. 26. Drag or resistance is in direction of the air-stream and is overcome by thrust.

The attitude and velocity of the airplane, in uniform flight, are such that the thrust and drag are exactly equal.

Center of resistance or drag. — Thrust is a force forward through the propeller shaft, applied at the **center of thrust** or **C. T.** The total drag of an airplane, the drag of wings and structure all included, may be considered as a single force backward in the direction of the air-stream applied at the **center of drag** or **C. D.**, which may coincide with the center of thrust as in Fig. 26, or may be a

¹ When thrust is inclined with reference to the flight path, drag is overcome by the component of thrust in the direction of the flight path. The small vertical component, when upward, supports part of the weight so that correspondingly less lift is required of the wing for sustentation; when downward, correspondingly more lift is required.

little above or below it. When the center of drag is above the center of thrust, there is a tendency for the machine to nose up when power is on, and when the center of drag is below the center of thrust there is a tendency for it to nose down. This affects longitudinal stability but in no way affects the value of drag or thrust.

Wing-drag and parasite drag. — Airplane drag falls under two heads: **wing-drag**, due to the wings; and **parasite drag**, due to all other parts of the airplane structure. (Parasite drag is sometimes called "structural drag" or "head drag.") The sum of the two is the **total drag**; thus,

Total Drag = Wing-drag + Parasite drag. In English units, drag is expressed in pounds.

Although expressed by very similar fundamental formulas, each varying as the square of the velocity, wing-drag and parasite drag have quite different characteristics: — wing-drag depends upon angle of attack, the variation of the coefficient of wing-drag K_D with angle of attack having been shown in Fig. 11, page 20, of the first chapter; parasite drag, on the other hand, is almost independent of angle of attack, except so far as angle of attack affects velocity.

Whereas parasite drag always increases as velocity is increased, wing-drag decreases as velocity is increased until a certain velocity is reached, after which it increases, as brought out in the following discussion.

On account of their different characteristics, wing-drag and parasite drag are considered separately.

WING-DRAG

Fundamental relation. — Wing-drag is equal to $K_D S V^2$,² as

² "Aeronautics in Theory and Experiment," Cowley and Levy, Chapter IV. A more complete analysis of drag, involving the "Theory of Dimensions," gives the following strictly correct equation for drag:

$$D = \rho S V^2 \cdot f \left(\frac{VL}{\mu} \right) \quad \text{Therefore } K_D = \rho \cdot f \left(\frac{VL}{\mu} \right).$$

ρ = the density of the fluid.

V = the relative velocity of the fluid.

L = the linear dimension of the body.

μ = the coefficient of viscosity of the fluid.

shown in the first chapter, and is fundamentally determined by this formula. A hasty inspection of the formula, however, might lead to the erroneous conclusion that wing-drag always increases with velocity. This indeed would be true, if K_D were constant; but in fact, as mentioned above, the changes in the value of K_D with angle of attack and velocity actually cause wing-drag to decrease through a certain range of velocities, and then to increase at high velocities.

Wing-drag is made up of two components, one of which changes with the angle of attack, the other being almost independent of the angle of attack. The first of these components is called **induced drag**.³ It results from the generation of lift, being zero at the angle of zero lift.

Application of hydrodynamic theory gives the induced drag coefficient by the following equation:

$$C_{D \text{ ind.}} = \frac{(C_L)^2}{\pi \times \text{aspect ratio}}.$$

The above equation is true, only for that range of angle of attack in which C_L varies directly with angle of attack.

The second component of the wing-drag is called **profile drag**. It is that part of the drag caused by the viscosity of the air, and by the turbulence and eddying of the air over the wing surfaces. That part of the profile drag, caused by the tendency of the air to stick to the wing, is called skin friction or viscous drag. That part of the profile drag, caused by the turbulence and eddying of the air, is called turbulence or eddy-making drag. For further discussion of skin friction, see the paragraph on parasite resistance.

The profile drag is dependent on the angle of attack, only inasmuch as the turbulence and eddy-making drag is increased at high angles of attack. Most of the increase in total drag, at high angles of attack, is caused by the increase in the induced drag coefficient, which increases as the square of the lift coefficient, so long as the lift coefficient varies directly as the angle of attack.

Since the induced drag coefficient is zero at the angle of zero lift,

³ See "Airplane Design," E. P. Warner, Chapter VI, pages 92 and 93.

the total drag coefficient, at this angle of attack, must equal the profile drag coefficient.

In the following discussion, K_D will mean the total drag coefficient, the sum of the profile and induced drag coefficients.

$$K_D = K_{D \text{ ind.}} + K_{D \text{ prof.}}$$

It should be remembered when using K_D that it is a variable, depending on angle of attack and velocity.

The variation of drag with velocity is best shown by some practical calculations and the plotting of curves.

Practical calculation. — Wing-drag can be calculated directly from the formula $K_D SV^2$. The calculation, however, can be made more readily from the L/D ratio for the particular wing in question. By definition

$$L/D \text{ ratio} = \text{Lift} \div \text{Wing-drag.}$$

Since Lift = Weight, in horizontal flight, we may write

$$\text{Wing-drag}^4 = \text{Weight} \div L/D \text{ ratio.}$$

To get the wing-drag, it is merely necessary to divide the known weight by the L/D ratio, the value of this ratio being taken from a table or curve for the particular wing-section.

Example. — For example, the weight of a loaded machine is 2000 lbs. The values for the L/D ratio for the wing used are given by the Table I, page 22, or by the corresponding curve, Fig. 12, page 21. Required to find the wing-drag and velocity for an angle of attack of 4° . From the table, $L/D = 16$ (approximately); hence

$$\text{Wing-drag} = 2000 \div 16 = 125 \text{ lbs.}$$

⁴ *Variation of wing-drag with angle of attack.* — The formula given above may also be written: —

$$\text{Wing-drag} = \text{Weight} \times D/L \text{ ratio.}$$

Wing-drag is, therefore, proportional to D/L . A curve giving the values for wing-drag for different angles of attack would be similar to the D/L curve, Fig. 12, page 21, the only difference between the two curves being the scale.

It is seen that every 16 lbs. of weight adds one pound to the wing-drag and will require one pound more thrust, and a corresponding increase in power, to overcome it.

To determine the velocity corresponding to the wing-drag in the above example, it is necessary to know the loading, for velocity depends upon loading. Thus, if the loading is $W/S = 6$ lbs. per sq. ft., using the formula of the preceding chapter, we have

$$\text{Velocity} = \sqrt{\frac{W}{SK_L}} = \sqrt{6 \div 0.00174} = 58.6 \text{ MPH.}$$

It is thus seen that when this particular wing-section is used in a machine weighing 2000 lbs., with loading 6 lbs. per sq. ft., the wing-drag is 125 lbs. at a velocity of 58.6 MPH.

Variation of wing-drag with velocity. — The variation of wing-drag with velocity for horizontal flight is well shown by the curves in Figs. 27, 28, 29, the points being calculated, in the manner just described, for different conditions of weight and loading.

It is seen that with increase of velocity (decrease of angle of attack) wing-drag always decreases until a certain velocity is reached, after which it again increases. The minimum velocity for any

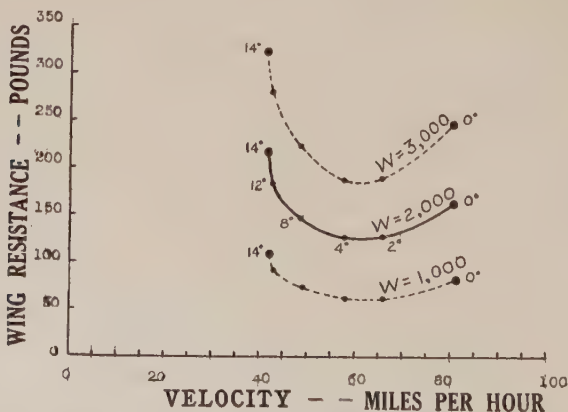


FIG. 27. Variation of wing-drag or wing-resistance with velocity, for horizontal flight. The three curves show effect of changing weight ($W = 1000, 2000$ and 3000 lbs.) when loading is kept constant ($W/S = 6$).

wing-section is obtained at the critical angle of attack; a greater angle of attack is beyond the range of practical flight. The critical angle for the particular wing-section here used is 14° but the curves have been calculated beyond 14° in some instances and are shown by dotted lines.

As the angle of attack is decreased to 0° , -1° , -2° , etc., wing-drag and velocity both rapidly increase and both would become infinite at the angle of attack that gives zero lift, — in this case at -3° .⁵

Effect of changing weight or loading. — In calculating the curves here shown, it was necessary to know the weight and loading, — inasmuch as $\text{wing-drag} = \text{weight} \div L/D$, and $\text{velocity} = \sqrt{\text{loading} \div K_L}$. Different curves for the variation of wing-drag with velocity are accordingly obtained by changing either weight or loading, or both, and in no other way, — it being understood that we are dealing with a particular wing-section flying in air of con-

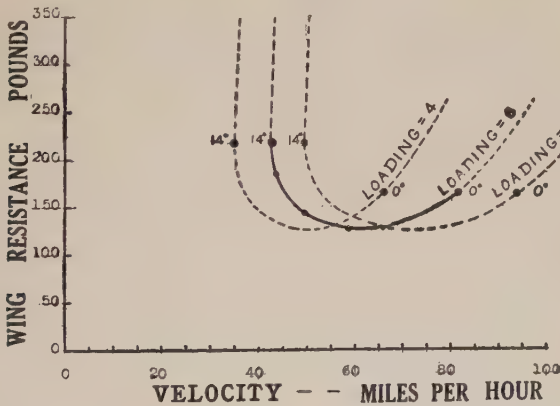


FIG. 28. Variation of wing-drag or wing-resistance with velocity, for horizontal flight. The three curves show effect of changing loading ($W/S = 4, 6$ and 8) when weight is kept constant ($W = 2000$ lbs.).

stant density. It will be found that all the curves are similar in form and differ only in scale.

⁵ The drag coefficient is finite and equal to the profile drag coefficient.

There are three cases:

- (1) when weight is changed and loading is kept constant;
- (2) when loading is changed and weight is kept constant;
- (3) when weight and loading are both changed.

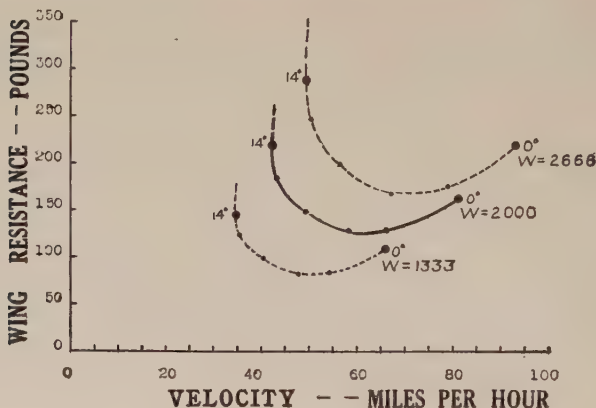


FIG. 29. Variation of wing-drag or wing-resistance with velocity, for horizontal flight. The three curves show effect of changing weight ($W = 1333, 2000$ and 2666 lbs.) and loading ($W/S = 4, 6$ and 8) in proportion, wing-area being constant.

(1) Effect of changing weight when loading is kept constant. —

In this case machines with greater weight also have greater wing-area, the loading remaining constant. Wing-drag for different machines is then directly proportional to weight. This is shown by the curves in Fig. 27 for three machines of different weight. Any point on these curves, corresponding to a particular angle of attack and velocity, is merely moved up for a heavier, or down for a lighter, weight machine; the heavier the machine, the greater is the wing-drag.

(1) Effect of changing loading when weight is kept constant. —

In this case weight is constant and wing-area is changed so as to give different loadings. Changing the loading, for a certain weight, changes the velocity corresponding to a certain angle of attack, but

does not change the amount of wing-drag, for that angle of attack. Hence, as shown by the curves in Fig. 28, a change of loading shifts to right or to left the point corresponding to a particular angle of attack, the velocity for that angle of attack being proportional to the square root of the loading.

The loading which gives the least wing-drag is different at different velocities. Thus, for the case shown by the three curves in Fig. 28 with loading 4, 6 and 8, up to about 55 miles per hour the wing-drag is least for a loading of 4; from 55 to 65 miles per hour, for a loading of 6; and above 65 miles per hour, for a loading of 8.

(3) Effect of changing both weight and loading, wing-area being constant. — This is a combination of the two preceding cases. A point on any of the curves is moved up or down in proportion to weight, and to right or left in proportion to the square root of the loading.

The three curves in Fig. 29 show the effect of changing weight and loading in proportion, wing-area remaining constant; this might be brought about by taking up the same machine at different times with different loads. It is to be noted that, at the same angle of attack, greater velocity is required to sustain the greater weight; or, at the same velocity, a greater angle of attack is required.

Variation of wing-section. — For a given wing-section there are the three possible ways just described for changing wing-drag — by changing the weight, the loading or both. If the wing-section is varied, the number of possible variations is infinite. There are many intermediate forms and variations that make an interesting field for study.

PARASITE DRAG OR RESISTANCE

Meaning and importance of parasite drag. — The wings of an airplane are its first essential, for they create the lift, but in creating lift they at the same time cause a wing-drag. Wing-drag, there-

fore, although not a cause of lift, is seen to be a necessary concomitant being the price paid for the lift.⁶ In a preceding example, it was shown that, in a given case, every sixteen pounds of lift must be paid for by one pound of wing-drag.

Unfortunately this is not all. In addition to wings an airplane must have other parts — body, landing gear, struts, wings, etc., — all of which have a drag; but unlike the wings, these parts do not contribute to the lift. The drag of these parts is, therefore, with some appropriateness called **parasite drag**.

One of the important problems in design is to make this parasite drag as low as possible, for while small at low velocities parasite

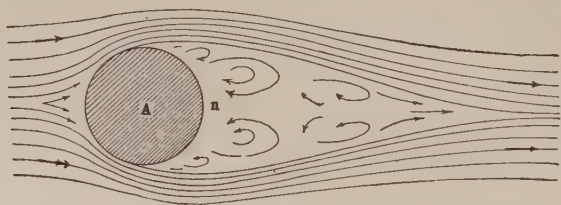


FIG. 30. Air flow past a cylindrical strut; air eddies and low pressure back of strut cause high drag.

drag is very great at high velocities, being perhaps fifty per cent. more than wing-drag at ordinary maximum flying velocities. In airplane flight, while about two-fifths of the power delivered through the propeller by the engine is used in pushing the wings through the air, **three-fifths of the power**, approximately, is used up in parasite drag. It is seen that parasite drag is the biggest obstacle to high-speed flight.

The nature of parasite drag. — Parasite drag, except for the almost negligible induced drag of certain parts of the airplane,⁷ is identical in nature with the profile drag of a wing. It is made up of skin friction or viscous drag and turbulence drag. The **viscous drag** is the drag that would occur if a flat plate, of the same area as

⁶ Strictly speaking, only the induced drag is the price paid for lift, the profile drag being present even when there is zero lift.

⁷ The tail control surfaces and the fuselage contribute slightly to the lift and therefore to the induced drag, at certain angles of attack.

the body under consideration, were moved edgeways through the air. This drag depends on the viscosity of the air, its resistance to having one layer move relative to another, and the amount of skin or area exposed. The layer of air adjacent to the moving body is stationary with respect to that body, as it adheres to the surface and is pulled along with it. The layers at a greater distance from the moving body have motion relative to the body and therefore relative to the layer of air which moves with the body. There must, therefore, be a shearing action between the layers of air surrounding the body. The viscosity of the air is a measure of its resistance to this shearing action.

If the flow of air past the body is smooth and unbroken the total drag, neglecting any induced drag, will be the drag of skin friction. If, however, the shape or surface of the body be such that there is turbulence and eddying, there will be turbulence drag as well as skin friction. Wings and tail surfaces, at small angles of attack, may give pure skin friction drag, (considering the profile drag only), for all practical considerations. There is always some turbulence drag no matter how well the stream lining is done, however.

In the other parts of the airplane, the fuselage, struts, wires, fittings, landing gear, engine, and radiator, the turbulence drag is of the greatest importance.

Factors affecting parasite drag.—The factors affecting the parasite drag on an airplane are the viscosity of the air, the shape of the airplane, the nature of the exposed surfaces of the airplane, the fineness ratio of the exposed parts, and the angle the airplane makes with the relative wind.

The effect of viscosity on parasite drag has been discussed in a previous paragraph.

Nature of the exposed surfaces.—Experimental work shows that, in general, roughening the surface of a body increases its profile drag. For this reason, all exposed parts of an airplane should have as smooth a finish as possible.

Streamline flow. — Fig. 30 shows the flow of air past a cylindrical strut or wire. Behind the strut there is a turbulent space and a partial vacuum, or negative pressure n , that tends to suck the strut along in the direction of the air-stream. A large part of the drag of the strut to motion through the air is thus due to this region of low pressure behind it.

In Fig. 31, the space behind the cylindrical strut A is partly filled by a piece B , so as to reduce the region of turbulence and low

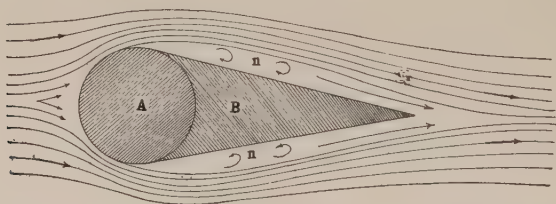


FIG. 31. Cylindrical strut A , backed up by a filler B of a form that reduces, but does not entirely eliminate, the air eddies and low pressure back of strut. Drag is thus reduced.

pressure. The resistance to motion through the air is thus greatly decreased. Struts are sometimes made in this manner, a piece A for strength being backed up by a piece B , of light material to save weight, and drag may be reduced in this way.

Although the shape shown in Fig. 31 is an improvement on the cylindrical strut, it is by no means the best, for it does not conform

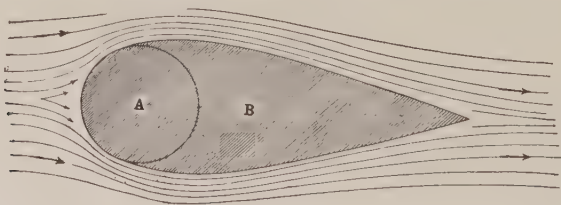


Fig. 32. Strut with air eddies and low pressure back of strut further reduced, by approaching a streamline form.

entirely to the streamline flow; there is still a turbulent region n , although this is much reduced. **The more nearly a body conforms to streamline flow the less is its drag, the turbulence and suction**

back of the body being then reduced to a minimum. Fig. 32 shows a strut more nearly conforming to streamline flow. This material added to reduce the drag is called **fairing**.

Only a little is gained by tapering the front side of a cylinder or strut. Note the blunt breast and tapering tail of a bird, and the shape of a fast swimming fish that can dart through the water with scarcely a ripple.

For low drag, wheels and body should be enclosed; these, as well as every strut and wire, should be streamlined so far as they can be. It should be remembered that a small cylindrical wire may offer much more drag than a larger wire that is well streamlined.

Effect of fineness ratio on drag of streamlined bodies. — The **fineness ratio** of a body, exposed to the wind, is the ratio of its length, parallel to the relative wind, to its maximum thickness, measured perpendicular to the relative wind. For a cylinder with its axis parallel to the relative wind, the fineness ratio would be the ratio of its length to its diameter.

It has been found that for any streamlined body there is a certain fineness ratio that gives minimum drag. The drag decreases at first with increase in fineness ratio, because of the decrease in turbulence drag as the turbulent space back of the body is filled up. As the fineness ratio is increased the area, over which the skin friction acts, increases as the square of the fineness ratio. This causes an increase in skin friction.

With a flat plate perpendicular to the relative wind, there is a minimum of skin friction and a maximum of turbulence drag. The point of minimum drag is at the fineness ratio at which the increase of skin friction, which increases about as the square of the fineness ratio,⁸ is greater than the decrease in turbulence drag. The best fineness ratio for any particular streamlined body must generally be determined by experiment.

Effect of inclination of the airplane to the relative wind. — In flight the airplane is seldom headed directly into the relative wind.

⁸ Doubling the fineness ratio quadruples the area exposed to skin friction.

This means that either the side or the bottom of the fuselage is exposed to the air-stream. The increase in parasite drag from this cause has been found to be from 2 to 30 per cent. of the normal parasite drag, depending on the angle the fuselage and struts make with the relative wind.

Inclination of the fuselage upward does not increase the drag so much as inclination sideways, because the width of the fuselage is usually less than its depth. With the fuselage inclined upward, a slight increase in lift is obtained, the fuselage acting as an airfoil having camber. This effect is so slight as to be negligible in most instances.

Parasite drag varies as the square of the velocity. — The law for parasite resistance is summed up in the statement, determined by experiment, that parasite drag varies as the square of the velocity. This applies not only to the separate parts ⁹ but also to an airplane as a whole. Thus, if a certain airplane has a parasite drag of 64 pounds when flying at 40 miles per hour, it will have a drag of 256 pounds at 80 miles per hour. In this case the parasite drag is $0.04 V^2$.

The curves in Fig. 33 show the values for parasite drag at different velocities for three cases, $D = 0.02 V^2$, $D = 0.04 V^2$ and $D = 0.06 V^2$, these illustrating the variation for a certain range of machines of moderate size.

Distribution of parasite drag. — Parasite resistance for a biplane is roughly distributed about as follows: — body, one-third; wires

⁹ There is an appreciable departure from the square law when the profile drag of a body is large compared with the direct impact or induced drag — the more so when the surface is rough and the fore-and-aft dimension of the body is large in proportion to the diameter — but practically it is simplest to neglect this and to assume the square law as strictly true. For only a small range in velocity, any error in this is inappreciable; for a large range, it may be necessary to take different values of the coefficient at different velocities.

If the square law were exact, the best stream-lining for one speed would be the best for all speeds. This, however, is found to be not always so; thus, a strut of one section may on test prove best at one speed, a strut of another section at some other speed.

and struts, one-third; tail and landing gear, one-third (about one-sixth for tail and one-sixth for landing gear).

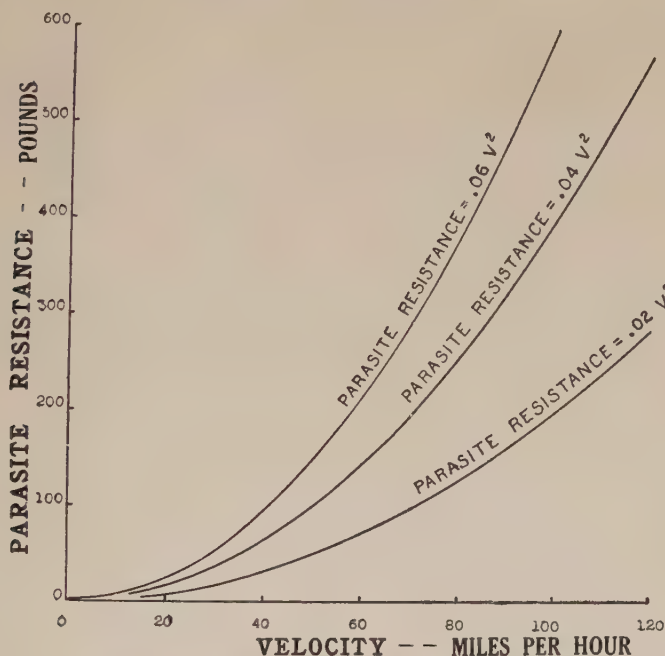


FIG. 33. Variation of parasite drag or resistance with velocity; the three curves show $D = 0.02 V^2$, $D = 0.04 V^2$ and $D = 0.06 V^2$.

Full scale tests,¹⁰ made on a Sperry Messenger airplane at 80 miles per hour, showed the drag distributed as follows:

	Pounds	Per cent.
Drag of the closed fuselage.....	16.0	24.4
Increase in drag by adding engine ...	11.3	17.3
Increase in drag due to cockpit.....	2.0	3.1
Increase in drag due to windshield...	2.0	3.1
Increase in drag due to tail surfaces .	8.0	12.3
Drag of landing gear.....	26.0	39.8
Total drag without wings and fittings	65.3	100.0

¹⁰ National Advisory Committee for Aeronautics Technical Note No. 271 Jan. 1928.

Since the results above are for the airplane without wings, the drag of the wing fittings and struts should be added to the above total to get the parasite drag for this airplane. The drag of the fittings and struts would be about equal to the drag of the bare fuselage.

It is to be especially noticed that the drag of the three cylinder air-cooled engine, with which this airplane was equipped, was almost as much as that of the bare fuselage. A reduction in the drag of the engine would greatly reduce the parasite drag of the airplane.

Water-cooled engines increase the parasite drag, also, as they must have radiators for cooling the circulating water. These radiators must be exposed to the wind. The amount of drag depends on the type of radiator and on its location on the airplane.

Increase of parasite drag due to propeller slip stream. — Back of the propeller the air is driven backward in what is called the *slip stream* or *propeller race*; in this slip stream the velocity of the air relative to the airplane is increased, say, 20 or 25 per cent. V^2 is thus increased about 50 per cent. The parasite drag of the tail and all parts of the structure in the slip stream is accordingly increased, let us say, 50 per cent. when the propeller is running. Approximate calculations may be made on this basis. Another approximate method is to consider that the increase of the total parasite drag due to the propeller slip stream is 10 per cent. To get accurate results, careful computation would be necessary.

A vast amount of data has been accumulated, and is becoming more and more available, for the drag of radiators, wheels, struts, wires, etc., of different forms and sizes.¹¹

Detrimental surface. — The structure of an airplane (other than wings) may, so far as parasite drag is concerned, be replaced by a

¹¹ See National Advisory Committee for Aeronautics Technical Notes: No. 280, March 1928, "Drag of Exposed Fittings and Surface Irregularities on Airplane Fuselages."

No. 279, March 1928, "Resistance of Stream-Line Wires."

so-called "equivalent flat plate" or "detrimental surface" s , perpendicular to the flight path. In terms of s ,

$$\text{Parasite drag} = ksV^2 = 0.003sV^2, \text{ approximately.}$$

Here k is approximately 0.003, when V is in miles per hour and s is the detrimental surface in square feet.

The total ks for a complete machine is the sum of the values of ks for each part, — radiators, struts, etc. Obviously every effort is made to make the total ks as small as possible.

Tests, on a typical air-cooled engine, showed that it had an equivalent flat plate area of 2.66 sq. ft. at 100 mi. per hr.¹²

The curves shown in Fig. 33 represent the parasite drag when ks equals 0.02, 0.04 and 0.06, corresponding to a detrimental surface s equal to 6.6, 13.3 and 20 sq. ft., respectively.

Note on terminology. — When there is no parasite drag, as in case of an airfoil alone, the whole drag is wing-drag and is commonly termed drag (formerly drift); the L/D ratio being termed the lift/drag ratio (formerly lift/drift). There is no confusion as to the meaning of drag in this case.

In the case of a complete machine, however, there has been difference in usage, drag being used to refer to wing-drag, alone, as well as to the total drag. To avoid possibility of confusion, the term wing-drag has been used throughout this book, being perfectly clear, although cumbersome.

SOME CONCLUSIONS

Three lines for improvement are suggested by the foregoing discussions: —

- (1) Reduce parasite drag.
- (2) Reduce weight.
- (3) Improve wing-section, so as to get a greater L/D ratio.

Wing-drag, which is equal to weight $\div L/D$, is reduced by (2) and (3). Most important are (1) and (2), as the improvement that can be made in L/D ratio is probably rather small.

¹² National Advisory Committee for Aeronautics Technical Note No. 292, July 1928.

Some means of reducing parasite drag. — Parasite resistance may be reduced by having as few fittings, wires, and struts exposed to the wind as possible. Internal bracing of wings has helped in this respect. All fittings, not capable of being enclosed in the fuselage or wings, should be streamlined, using the fineness ratio giving the least drag. Retractable landing gear, of a type comparable to the present types in weight and durability, would cut down the parasite drag greatly. The use of generous fillets, where exposed surfaces join each other, tends to prevent eddying and turbulence, thus reducing the drag. Smooth finish on all exposed surfaces also reduces the drag.

Some means of increasing strength without added weight. — An increase in strength and durability and a decrease in weight of the airplane have been accomplished by the application of newly developed methods of construction of airplanes. In the modern fuselage, practically no wood is used. The fuselage is built up of seamless steel tubing, welded at the joints, and braced with steel wires.

Substitution of tubing made of a steel, chromium, and molybdenum alloy, while not increasing the weight of the plane, has added about fifty per cent. to the fuselage strength.

Metal is used for wing spars only in large airplanes. The metal used for this purpose is an aluminum alloy, having a strength comparable to that of steel and a weight one-third that of steel. This alloy weighs about seven times as much as wood; but because of its high strength, a wing can be made of it weighing less than a wooden wing of equal strength. The weight of engine parts has also been reduced by using aluminum alloys in engine construction. Improved fuel economy is important as a means for reducing weight. A more efficient engine, even though heavier, may reduce the total weight of engine and fuel. Army engineers have found that the use of ethylene glycol, instead of water, for cooling airplane engines makes it possible to reduce the size and weight of the radiator 75 per cent.

CHAPTER IV

THRUST REQUIRED

That the total drag, impeding an airplane in flight, is the sum of the wing-drag and the parasite drag, has been explained in Chapter III. In that chapter curves were given, showing how wing-drag and parasite drag vary with airplane velocity relative to the air. In Fig. 26 it was seen that drag acts in the direction of the air-stream and is overcome by thrust, a force acting in the opposite direction to drag. Thrust is obtained by means of a power plant and a propeller, as discussed later in Chapter VI. The value of the thrust varies with both engine or propeller speed and the airplane velocity relative to the air.

The thrust required, to maintain horizontal flight at any given velocity, is determined by the total airplane drag at that velocity.

In horizontal flight thrust is equal to drag. — Uniform horizontal flight can be maintained only when the thrust ¹ and the opposing drag are exactly equal. If the two are not equal, the machine assumes an inclined flight path (as explained ² in Chapter II). The machine may be restored to its horizontal path by elevator control and corresponding change of angle of attack, but in this case the machine assumes a different velocity, — a velocity at which the drag is just equal to the thrust.

Thrust and drag may be made equal in another way, namely, by increasing or decreasing the thrust from the propeller by speeding up or slowing down the engine by throttle control. In any event, whether accomplished by elevator or by throttle control — or by both — the flight path is maintained horizontal by keeping thrust and drag exactly equal. Inclined flight will be discussed later.

¹ When thrust is inclined with respect to the flight path, drag is balanced by a component of thrust in line with drag, as shown in a later paragraph.

² See also Chapters VII and VIII.

For uniform, horizontal flight, therefore, we may write:

$$\begin{aligned}\text{Thrust} &= \text{Total Drag} \\ &= \text{Wing-drag} + \text{Parasite Drag}.\end{aligned}$$

Variation of thrust with velocity. — Curves showing the variation of wing-drag and parasite drag with velocity have already been given. The curve for the variation of total drag or thrust with velocity is simply found, therefore, by adding the ordinates of the two curves, as in Fig. 34.

It is seen that at low velocities parasite drag is very small, being much less than wing-drag and of little consequence. As velocity increases (and angle of attack decreases) wing-drag at first decreases and then increases; on the other hand, parasite drag steadily increases as the square of the velocity so that, except at low velocities, parasite drag is greater than wing-drag, — perhaps fifty per cent. greater under usual flying conditions.

Minimum thrust or drag. — The total drag of an airplane has a minimum value at a certain definite velocity and angle of attack, as shown by the curve in Fig. 34. It will be shown later that this angle of attack and velocity will give the “best glide,” — the longest glide and smallest gliding angle when the power is cut off. (See a later chapter, under Gliding, where it is shown that the sine of the gliding angle is equal to D/W ; hence, when D is a minimum the gliding angle is a minimum.)

Thrust as affected by weight, loading and parasite drag. — In the preceding chapter it was shown that for a given wing-section there are three possible changes that affect wing-drag, namely, change of weight, change of loading and change of both weight and loading. Any increase or decrease in wing-drag, due to these changes, makes a corresponding increase or decrease in the total drag or thrust. So, likewise, does any change in parasite drag.

There are, accordingly, four changes affecting thrust, as shown in the following paragraphs.

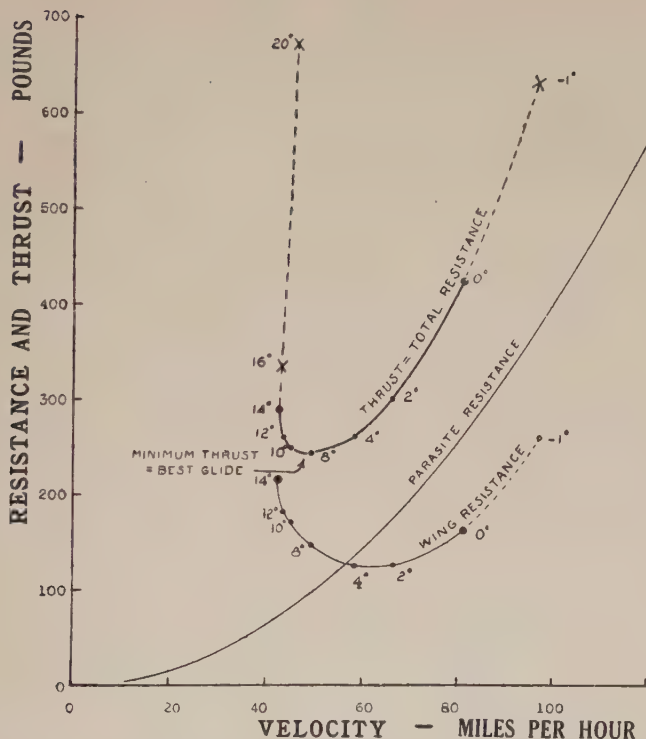


FIG. 34. Total resistance (total drag) or thrust is the sum of wing-resistance (wing-drag) and parasite resistance (parasite drag). The curves represent case when $W = 2000$ lbs.; $W/S = 6$; parasite resistance (parasite drag) $= 0.04 V^2$.

(1) **Effect on thrust of change of weight when loading is constant.** — Fig. 35 (corresponding to Fig. 27) shows the variation of thrust with velocity of machines of three different weights with loading constant. The greater weight requires the greater thrust, but (on account of the parasite drag being assumed constant) the increase of thrust is not in proportion to the increase in weight. It will be noted that the points for minimum thrust (corresponding to best glide) for the three curves, do not occur at the same velocity and angle of attack.

(2) **Effect on thrust of change of loading when weight is constant.** — In this case, wing-area is changed and the weight is constant so as to give different loadings. The effect of this change

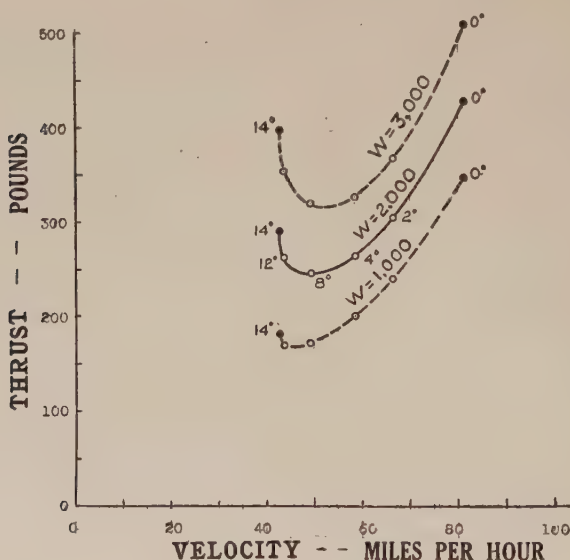


FIG. 35. Variation of thrust with velocity. The three curves show effect of changing weight ($W = 1000, 2000$ and 3000 lbs.) when loading is kept constant ($W/S = 6$); parasite resistance (parasite drag) $= 0.04 V^2$.

upon thrust is shown by the three curves in Fig. 36, which corresponds to Fig. 28 in the preceding chapter. Generally speaking, it is desirable to employ a loading that requires the least thrust. It is seen that the best loading depends upon the velocity, a greater loading being best at higher velocities. Thus, for the cases here shown with loadings 4, 6 and 8 lbs. per sq. ft., a loading of 4 is best (approximately) up to 55 miles per hour, a loading of 6 up to 65 miles per hour and a loading of 8 for higher velocities.

(3) **Effect on thrust of change of weight when loading is changed in proportion to weight, wing-area being constant.** — The three curves in Fig. 37 (corresponding to Fig. 29) show the effect upon

thrust when the same machine is flown with loads of different weight.

If the same velocity is to be maintained, it is seen from the curves that, when weight is increased, a greater thrust is required and it is necessary to fly at a larger angle of attack. The larger angle of attack, which increases the lift, also increases the drag and so requires greater thrust.

On the other hand, if the machine is to be flown at a certain constant angle of attack, when the weight is increased it must fly at a higher velocity. Obviously a higher velocity is necessary to support the increased weight.

(4) **Effect on thrust of change of parasite drag.** — When parasite drag is increased, the total drag and thrust are correspondingly increased, as shown by the three curves in Fig. 38 (corresponding to Fig. 33).

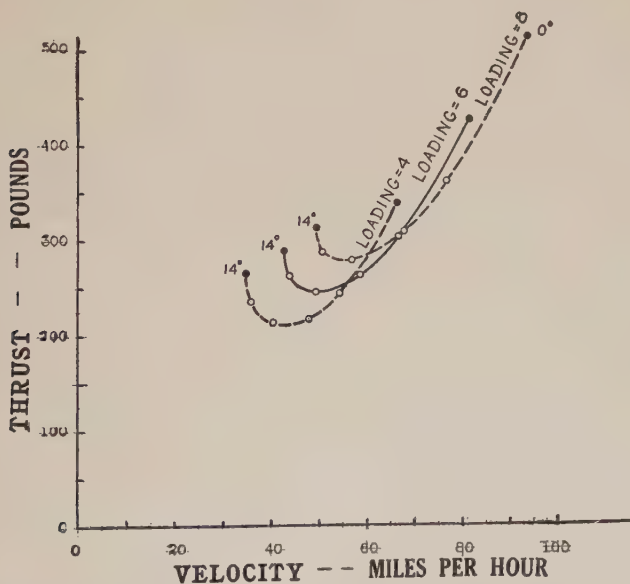


FIG. 36. Variation of thrust with velocity. The three curves show effect of changing loading ($W/S = 4, 6$ and 8) when weight is kept constant ($W = 2000$ lbs.); parasite resistance (parasite drag) $= 0.04 V^2$.

In all the four cases discussed above and illustrated in Figs. 35-38, the conditions which give the least drag (best glide) may be

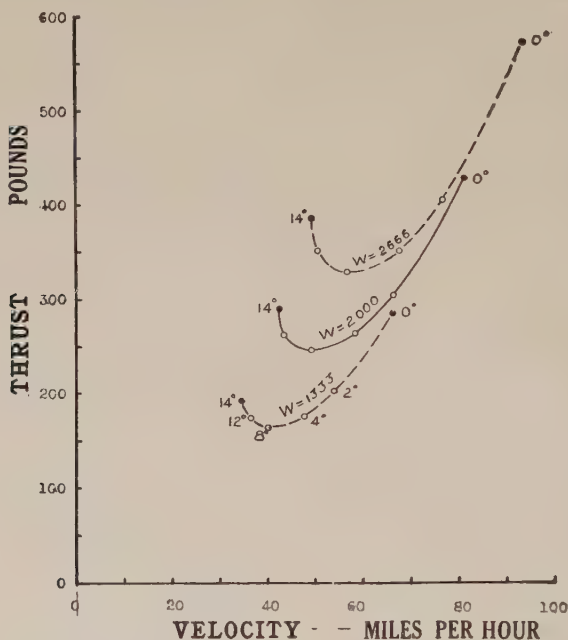


FIG. 37. Variation of thrust with velocity. The three curves show effect of changing weight ($W = 1333, 2000$ and 2666 lbs.) and loading in proportion ($W/S = 4, 6$ and 8), wing-area being constant; parasite resistance (parasite drag) $= 0.04 V^2$.

noted. The velocity for minimum drag is changed by any change of weight, loading or parasitic drag. The velocity for minimum drag is further discussed in connection with Fig. 43a in the next chapter.

Inclination of propeller thrust. — Although propeller thrust is always in the general direction of airplane flight, only rarely is it precisely in that direction. In fact, as the attitude of a machine changes while flying, the direction of the thrust with respect to the flight path changes. The direction of thrust is along the propeller

axis and becomes inclined up or down as the machine noses up or noses down.

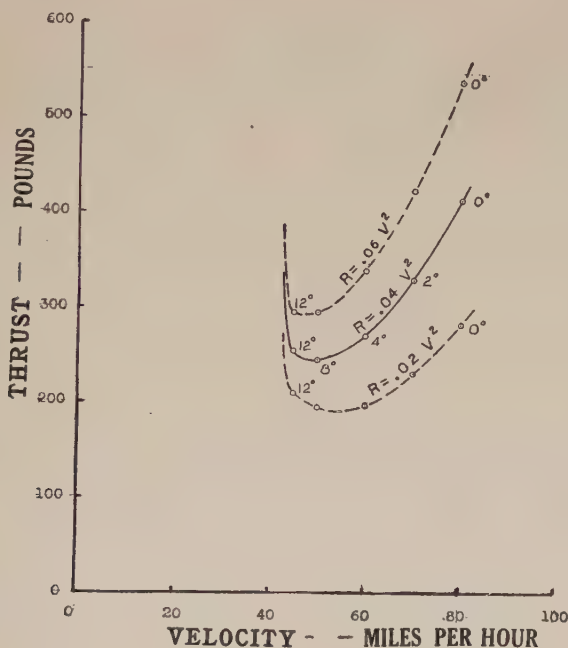


FIG. 38. Variation of thrust with velocity. The three curves show effect of changing parasite resistance (parasite drag) ($R = 0.02 V^2$, $D = 0.04 V^2$ and $R = 0.06 V^2$); weight and loading constant ($W = 2000$ lbs.; $W/S = 6$).

In horizontal flight, thrust may then be horizontal, inclined upward or inclined downward, the three cases being illustrated in Figs. 38a, 38b and 38c. The two air forces, drag D and lift L , may in each case be combined into a single force F as shown; while thrust T and weight W may, in a like manner, be combined into a single equal and opposite force F' . The total thrust may be considered as made up of two components, not shown in the diagrams: a horizontal component T_H along the flight path, equal and opposite to drag (this component is horizontal in horizontal flight only) and a vertical component, T_V , perpendicular to the flight path.

When the thrust is horizontal (in horizontal flight) it is seen, Fig. 38a, that $T = D$ and $L = W$, there being no vertical component to the thrust.

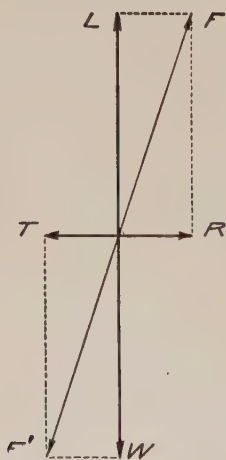
When the thrust is inclined upward, Fig. 38b, the vertical component T_v aids the lift in supporting the weight; more weight can be carried with the same lift, or the same weight can be carried with less lift. Thus,

$$W = L + T_v ; L = W - T_v.$$

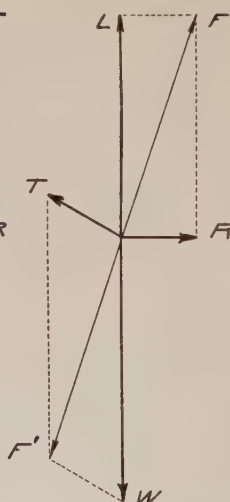
When the thrust is inclined downward, Fig. 38c, the vertical component T_v opposes the lift; either less weight can be supported or more lift must be obtained. Thus,

$$W = L - T_v ; L = W + T_v.$$

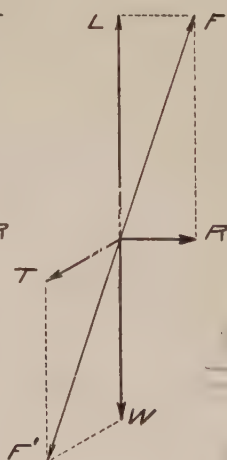
From the foregoing, it is seen that inclining the thrust slightly upward reduces the thrust necessary to support a given weight.



38a



38b



38c

FIG. 38a. Thrust in same direction as resistance.

FIG. 38b. Thrust inclined upward.

FIG. 38c. Thrust inclined downward

It can be shown ² that the ratio of thrust to weight, T/W , is a minimum when the thrust is inclined upward at a small angle whose tangent is D/L so that the thrust is perpendicular to the total resultant air force F . For a larger angle of inclination T/W increases, until $T/W = 1$, when the thrust is vertical as in a helicopter. As an example, if $D/L = 0.14$, the ratio of thrust to weight is a minimum when the thrust is inclined upward 8 degrees. (Tangent $8^\circ = 0.14$.)

Calculation of velocity. — The fundamental aerodynamic equation for lift ³ is $L = K_L S V^2$, whence, by substituting $W \pm T_v$ for L , we have for velocity in horizontal ⁴ flight

$$\text{and } V = \sqrt{\frac{W}{SK_L}}.$$

$$V = \sqrt{\frac{W \pm T_v}{SK_L}}.$$

When T_v is small, or zero, the formula takes the simpler form $\sqrt{\frac{W}{SK_L}}$, used in calculating the curves in this chapter and elsewhere. It should be borne in mind, however, that T_v is zero only for one particular angle of attack.

Airplane thrust compared with traction coefficient of other vehicles. — The thrust necessary for propelling an airplane is much greater than the "traction coefficient" or "draw-bar-pull" of other vehicles of locomotion. In an airplane, wing-resistance alone is, let us say, from 5 per cent. to 8 per cent. of the weight of the machine (corresponding to $L/D = 20$ to 12.5). To this is added the

² In the triangle formed by W , F' and T , when W and the angle between F' and W have given values, T is evidently a minimum when perpendicular to F' and F . The angle between T and the horizontal is then equal to the angle between F and L , the tangent of which is D/L .

³ The wing surfaces give most of the lift, but other surfaces may contribute; see note on "Modification in complete Machine," in Chapter II.

⁴ In oblique flight, weight is sustained by the vertical component of lift, plus or minus the vertical components of thrust and resistance; $W = L_v \pm T_v \pm D_v$. The last two terms usually have opposite signs. For practical purposes, when the flight path does not depart far from the horizontal, $W = L$.

parasite drag, making the total drag or thrust, in some common types of airplane, as much as 10 per cent. to 15 per cent. of the weight; that is $D/W = 0.10$ to 0.15 .

The traction coefficient of water craft is less than 1 per cent. The traction coefficient of trains on level rails is between 1 and 2 per cent., and of road vehicles on level pavement only a little more. The drag of a dirigible balloon has been reported as between 4 and 6 per cent.

An average value for the force required to tow an automobile (analagous to the thrust required for an airplane) over a level, paved road can be found by the following equation:

$$\text{Towing force} = 0.01W + 0.0375V^2.$$

W is the weight of the car in pounds and V is its velocity relative to the wind in miles per hour. The first term in the right hand side of the equation accounts for the friction or rolling loss at the road surface. The second term on the right hand side accounts for the windage or wind drag on the car.

The towing force required for a car weighing 4000 pounds, traveling on a level road at 60 miles per hour, as given by the above equation, would be 175 pounds. This corresponds to a traction coefficient of .0438.

A comparison of the traction coefficients of airplanes and other vehicles shows that the airplane cannot compete with other vehicles in regard to low thrust. There are, however, some advantages of the airplane, which make it a superior means of transportation for certain purposes. Its high speed reduces the time consumed in traveling. The air, a universal right-of-way, extends everywhere and is always ready for use without cost for maintenance or construction.

CHAPTER V

POWER REQUIRED

A method of determining the **power required** to drive an airplane through the air in horizontal flight will be developed in this chapter. The **power available** from the engine and propeller, its relation to the power required, and the effect of altitude on power will be considered in the following chapters.

Calculation of power required. — The thrust required to propel an airplane through the air at any velocity may be computed, as explained in the previous chapter, if the total drag characteristic curve of the airplane is known. The power consumed in propelling the airplane at any speed may then be determined, since power is proportional to the product of thrust and velocity. Thus, when thrust is expressed in pounds and velocity is expressed in miles per hour,

$$\text{Horse Power}^1 = \frac{\text{Thrust} \times \text{Velocity}}{375}.$$

This means that each pound of drag requires 1/375 H.P. to overcome it for each mile per hour of velocity.

Variation of power required with velocity. — In the preceding chapter, the curves in Figs. 34–38 show the variation with velocity of the *thrust* required for horizontal flight. The corresponding curves for *power* required, calculated from the thrust curves in the manner just described, are shown in Figs. 39–43.

¹ By definition,

$$\begin{aligned} \text{Horse Power} &= \frac{\text{ft. lbs. per min.}}{33000} \\ &= \frac{\text{lbs.} \times \text{miles per hr.}}{33000} \times \frac{5280}{60} = \frac{\text{lbs.} \times \text{miles per hr.}}{375} \end{aligned}$$

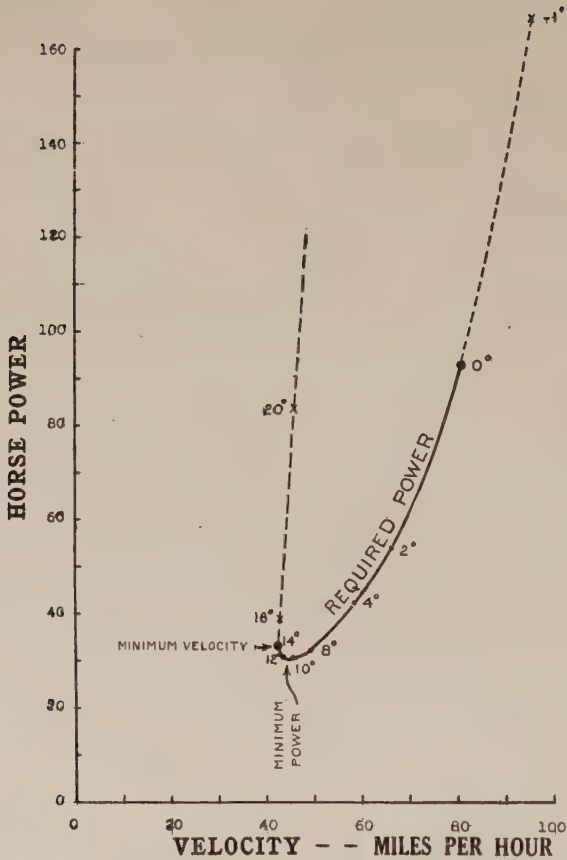


FIG. 39. Power required at different velocities, when $W = 2000$ lbs.; $W/S = 6$; parasite resistance (parasite drag) $= 0.04V^2$.

The curve for the power required by an airplane in horizontal flight is seen to be a U-shaped curve having a definite minimum value at a certain velocity and corresponding angle of attack. It is interesting to note, therefore, that when an airplane is flying at a certain velocity, — namely, the velocity that requires minimum power — more power will be required to fly either slower or faster.

Under usual conditions, all flying is at a higher velocity than that which corresponds to minimum power and is at a smaller angle of

attack. In this usual working range, therefore, in order to go faster in horizontal flight the pilot opens the throttle and decreases the angle of attack; to go slower, he closes the throttle and increases the angle of attack.

When flying at a very *low velocity*, however, — a velocity lower than that corresponding to minimum power, — *the conditions of control are reversed*, so far as the throttle is concerned. To go slower in horizontal flight, more power is required; the pilot must open the throttle and at the same time increase the angle of attack. These conditions (flying with low velocity and large angle of attack and with reversed throttle control) are not usual flying conditions; under such conditions, special care on the part of the pilot is necessary, for a stall is imminent and, furthermore, the airplane loses much of its stability.

The relations between power required, velocity and angle of at-

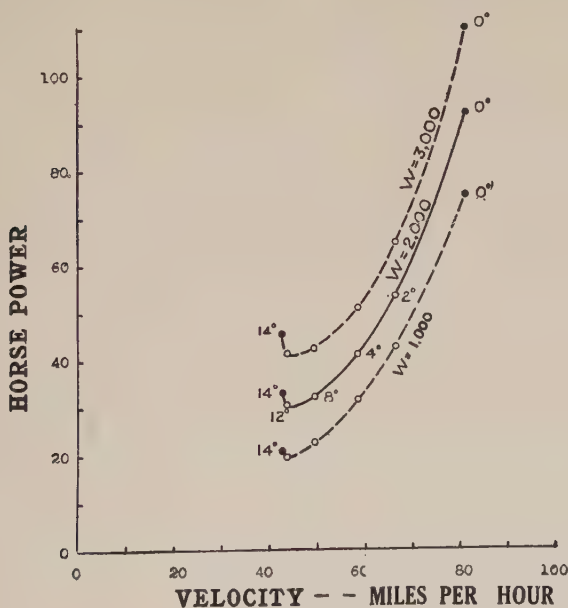


FIG. 40. Variation of power required with velocity. The three curves show effect of changing weight ($W = 1000, 2000$ and 3000 lbs.) when loading is kept constant ($W/S = 6$); parasite resistance (parasite drag) $= 0.04V^2$.

tack will be more fully considered later in Chapter VII, after the chapter on Power Available.

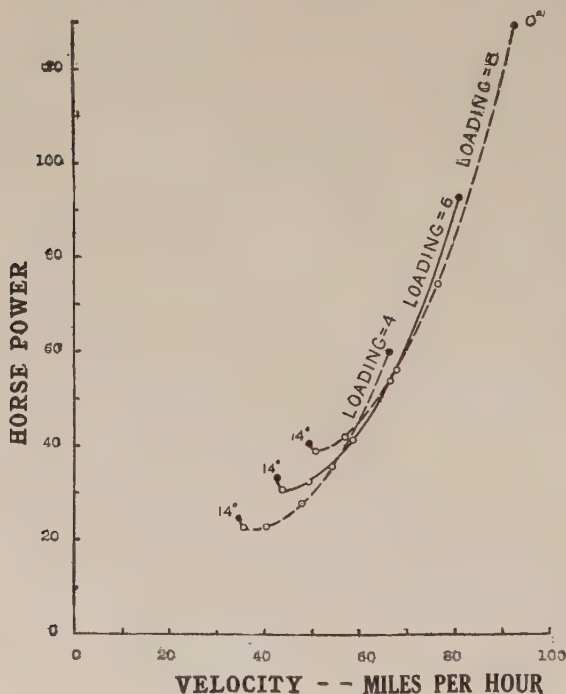


FIG. 41. Variation of power required with velocity. The three curves show effect of changing loading ($W/S = 4, 6$ and 8) when weight is kept constant ($W = 2000$ lbs.); parasite resistance (parasite drag) = 0.041^2 .

Power as affected by weight, loading and parasite drag. — The three curves in Fig. 40 (corresponding to Figs. 35 and 27) show how power required is affected by change of weight, when loading is constant. For the same velocity, the heavier machine requires more power; for the same power, the heavier machine flies at less velocity and at a greater angle of attack.

The curves in Fig. 41 (corresponding to Figs. 36 and 28) show the effect on power of change of loading when weight is constant. For each velocity, there is a certain loading that requires least

power. At low velocities, a small loading is best; while at higher velocities the least power is required by a greater loading, that is, by a smaller wing-area.

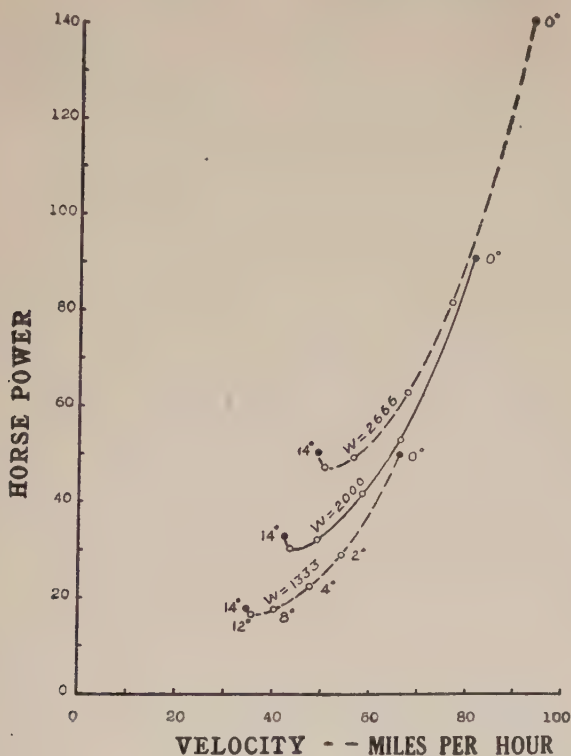


FIG. 42. Variation of power required with velocity. The three curves show effect of changing weight ($W = 1333, 2000$ and 2666 lbs.) and loading in proportion ($W/S = 4, 6$ and 8), wing-area being constant; parasite resistance (parasite drag) $= 0.04V^2$.

The curves in Fig. 42 (corresponding to Figs. 37 and 29) show the power required when the same machine is flown with three different weights, the loading in each case being in proportion to the weight. For any given angle of attack, the greater weight requires, to sustain it, a greater velocity and more power.

The change of power in the preceding three cases was brought

about by a change of wing-drag due to a change of weight or loading or both; parasite drag at each velocity was constant. The curves in Fig. 43 (corresponding to Figs. 38 and 33) show how the power required is increased by an increase of parasite drag; in this

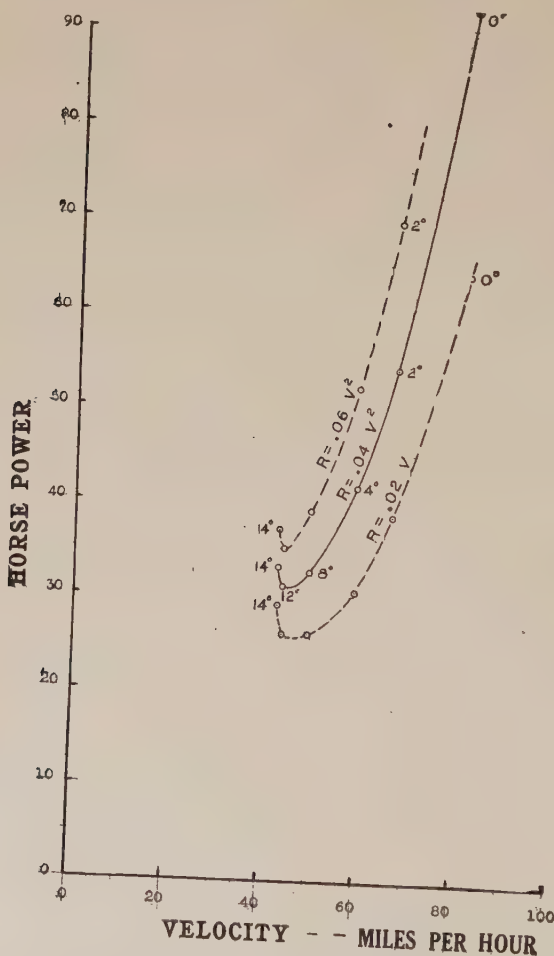


FIG. 43. Variation of power required with velocity. The three curves show effect of changing parasite resistance (parasite drag) ($R = 0.02 V^2$, $R = 0.04 V^2$ and $R = 0.06 V^2$); weight and loading constant ($W = 2000$ lbs.; $W/S = 6$).

case the angle of attack and the wing-drag at each velocity are constant.

Minimum thrust ² is shown by the point of tangency on the power curve of a straight line drawn from the origin. — From the first paragraph of this chapter it is seen that

$$\text{Thrust} = 375 \times \frac{\text{Horse Power}}{\text{Velocity}}.$$

Let a'' be any point on the curve for power required, Fig. 43a. The corresponding thrust required, being proportional to horse

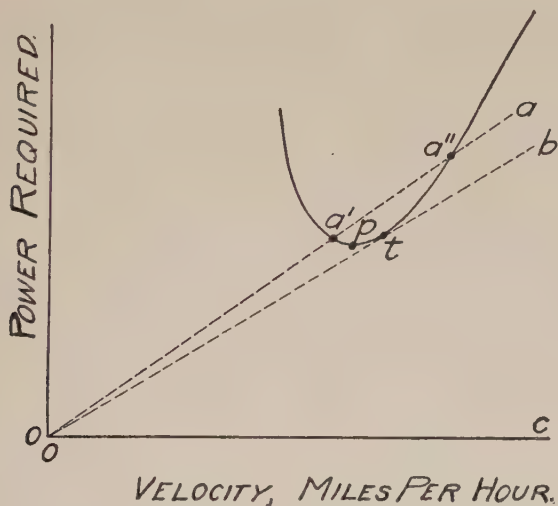


FIG 43a. Any line oa drawn from the origin intersects the power curve at points of equal thrust, $a' a''$. Minimum thrust is obtained at t , where the line ob is tangent to the power curve.

power divided by velocity, is evidently proportional to the tangent of the angle aoc . It follows that, if a straight line oa is drawn from the origin so as to intersect the power curve at two points, a' and a'' the thrust required at these two points will be equal.

If the line is swung downward, so that the angle aoc is smaller,

² As thrust and drag are equal in horizontal flight, minimum thrust is here equivalent to minimum drag.

the corresponding thrust becomes smaller. Minimum thrust is required at the point t , at which a straight line ob drawn from the origin is tangent to the curve.

It is seen that for minimum thrust t , an airplane must fly at a higher velocity and a smaller angle of attack than for minimum power p . As discussed later under Gliding, t also shows the condition for longest glide and minimum gliding angle.

Speed requiring least energy expenditure when flying a given distance. — In flying a distance d , the total energy expended or total work done is $t \times d$, being proportional to force and distance. If t is the thrust in pounds and d is the distance in feet, the above expression gives the work done in foot-pounds. In flying a given distance, the energy expended is, accordingly, proportional to the thrust and must be a minimum when the thrust is a minimum. *Therefore, considering energy expenditure only, the most economical velocity to maintain, when flying a given distance, is the velocity requiring minimum thrust.*

Speed requiring least energy expenditure when flying for a given time. — The work done or energy expended, in flying for a given time, is equal to the product of the power required and length of flying time. If the power required is expressed in foot-pounds per minute and the flying time in minutes, the above product will be the work done in foot-pounds.

For a given time, this product will be a minimum when the power required is a minimum. *Therefore, considering energy expenditure only, the most economical velocity to maintain, when flying for a given time, is the velocity requiring minimum power.*

Most economical speed for the airplane. — The most economical speed for the airplane is the speed at which the fuel consumption per unit of energy expended is a minimum. Whether the fuel consumption per unit of energy expended is a minimum for the speeds cited above, for minimum energy expenditure, depends upon the characteristics of the engine and propeller, as well as upon the aerodynamic relations in the preceding paragraphs.

From the curve, Fig. 43a, it is seen that a velocity higher or lower than the one corresponding to t , requires a greater expenditure of energy, when flying a given distance. At a lower velocity than at t , a small increase in power causes a large increase in velocity. Velocities much lower than at t are usually undesirable because of the larger angles of attack required for flight in this range, with the subsequent danger of stalling, described in a preceding paragraph.

At velocities higher than at t a large increase in power is necessary to cause a small increase in velocity. For this reason it is usually undesirable to fly at velocities much higher than that indicated by a'' , the power required increasing more and more rapidly as the velocity is increased.

The velocity for highest total efficiency can be obtained by combining the aerodynamic efficiency and the engine and propeller efficiency curves. The point of maximum total efficiency, as well as aerodynamic efficiency, will occur at t only if the engine and propeller combination is designed for maximum efficiency at this point.

The power plant, propeller, and the amount of power available, which have not yet been considered, will be discussed in the following chapter.

CHAPTER VI

POWER AVAILABLE FROM THE AIR PROPELLER AND THE AIRPLANE ENGINE

In the last chapter we saw that the **power required** to propel an airplane at different velocities depended on the design or structure of the airplane, varying as the product of total airplane drag and airplane velocity. Thus the power required is independent of the source of power and the amount of power available except in so far as the power plant and propeller affect the total airplane drag and airplane velocity. The curves for power required were given and discussed in the preceding chapter.

The power available for propelling the airplane, called **power available** or **thrust horse power**, does depend entirely upon the air propeller and the airplane engine. The propeller provides the thrust or driving power for the airplane, the propeller in turn being driven by the airplane engine. The thrust horse power is the product of thrust and airplane velocity divided by 375, if thrust is measured in pounds and velocity is in miles per hour. The propeller and the airplane engine may be directly connected, the propeller being mounted on the engine crank-shaft, or they may be indirectly connected by means of a set of gears which reduce the speed of the propeller below the speed of the engine. With either manner of connection the operating characteristics of the engine and propeller depend one upon the other. The power absorbed by the propeller must exactly equal the power delivered by the engine. The speed of the propeller equals the speed of the engine if directly connected; it is a fraction of the engine speed if connected by reducing gears.

A description of the types of airplane engines in common use will be found in a later chapter. An outline of the characteristics of the engine which affect the power available in airplane flight will

be given in the following paragraphs. This will be followed by a more complete discussion of the air propeller, its *Conditions of Operation*, its *Characteristics*, and its *Theory*.

THE AIRPLANE ENGINE

The gas engine is the airplane engine in general use on account of light weight. — The internal combustion engine — or the “gas engine” as it is more popularly known — made flight possible; and, although some of its characteristics are not the best for airplane flight, it meets the important requirement of *low weight per horse power*. Each year airplane engines have been made of greater power and less weight per horse power, a great advance being made by the Liberty motor (1918) which gave 450 H.P. with a weight of only 1.8 lbs. per H.P.

Particularly undesirable is the decrease in the power developed by a gas engine at high altitudes, the power developed being in direct proportion to the density of the air, as discussed in a later chapter. At an altitude of about 20,000 feet, only half as much power is developed as near the ground. The use of superchargers on airplane engines, to supply air to the engine at sea level density, has reduced this difficulty only with an increase in weight and complexity of the power plant.

Although other types of engine may hereafter be introduced, — possibly in huge aircraft requiring many thousand horse power, — the gas engine may be looked upon as *the standard type* of airplane engine and it alone needs be here considered.

Size and weight of engines. — The original motor of the Wright Brothers, used in the first airplane flight in 1903, gave 12 horse power, with a weight of 12.7 lbs. per horse power. The development of the airplane engine since then is shown by the following table. The numbers, except for 1903 and 1918, are average values for the principal engines for each year.

Year	1903	1910	1914	1916	1918	1929	1929 ¹
Horse power	12	54	112	185	450	608	186
Weight, lbs.	152	309	437	570	825	926	411
Lbs. per H.P.	12.7	5.7	3.9	3.1	1.8	1.53	2.2

Since the World War the air-cooled engine has gained favor very rapidly until in 1929 it is used almost exclusively throughout the United States. The weights given above for 1929 are therefore divided, the weights of the air-cooled and of the water-cooled engines being given separately. In comparing these weights and the weights given for previous years, all preceding weights being for water-cooled engines, it should be remembered that the weights given for water-cooled engines are the dry weights. To these weights should be added the weights of radiator and cooling water as these are essentials to proper cooling and operation of the engine. The weight of the water-cooled engine then becomes about 3 to 3.5 pounds per horse power.

Variation of engine power with speed. — The power developed by a gas engine, with throttle wide open or in other constant position, increases in proportion to the number of explosions in a given time and hence in proportion to the number of revolutions per minute, which hereafter will be referred to as the speed N . For a considerable range of speed this proportionality is quite close, power increasing in direct proportion ² to speed; but for higher speeds the power increases less rapidly, and finally a speed is reached at which the power is a maximum and beyond which the power falls off. This falling off in power is due largely to the fact that the fuel-charge received in the cylinders for each explosion is reduced at high speeds on account of the increased friction through ports and passages.

¹ These values are the average weights and horse powers for the air-cooled engines. The preceding column contains the values for the water-cooled engines.

² Power varies as torque $\times$ speed. When power varies in direct proportion to speed, torque is constant. The torque in a gas engine is nearly constant through the working range. As the power curve falls off from a straight line, the torque decreases.

The variation of power with speed for a typical engine ³ is shown in Fig. 44, in which the solid curve shows the brake horse power when the throttle is wide open. It is seen that power increases very nearly in proportion to speed until, in this case, a maximum of 106 H.P. is reached at a speed of 1240 R.P.M.

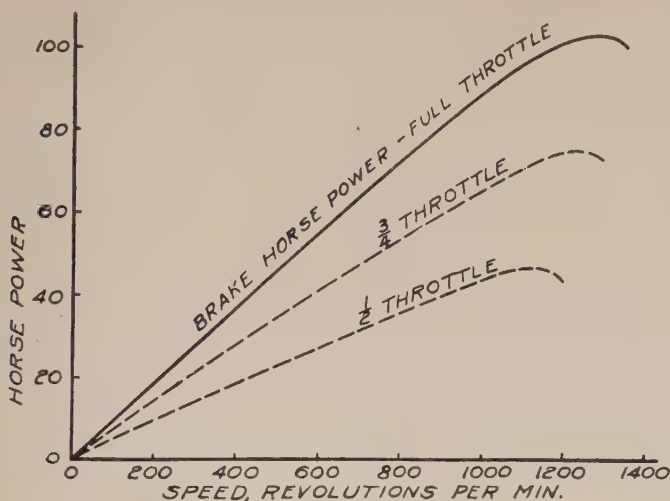


FIG. 44. Variation of brake horse power of a typical gas engine with speed. Dotted curves show reduction of power by throttle control.

Mechanical efficiency. — The entire power developed by the explosions in the cylinders of a gas engine is called the **indicated horse power** or **I. H. P.** Some of this power, however, is wasted in friction and other losses within the engine, so that the useful delivered horse power — called the **brake horse power** or **B. H. P.** — is, let us say, 10 or 15 per cent. less than the indicated horse power.

The mechanical efficiency of the engine is the ratio of the brake horse power to the indicated horse power; thus when the losses are 10 or 15 per cent., the mechanical efficiency is 90 or 85 per cent. The efficiency of an engine, as well as its power, varies with the

³ One hundred H. P. Gnome Monosoupape Motor. This particular motor is no longer made. Its performance, however, may be taken as typical.

speed at which the engine is run. The efficiency is low at low speed and at very high speed (i.e., when the power delivered is low) and is nearly a maximum when power is a maximum. The speed for maximum efficiency is a little lower than the speed for maximum power, but the efficiency remains high (within a few per cent. of its maximum value) for a wide range of speed — a range, let us say, of twenty or thirty per cent. (In Fig. 44, this range extends roughly from the beginning of the word Throttle to the point of maximum power.)

Range of engine speed. — The best speed for engine operation is no one precise speed but extends through a moderate range of values just below the speed for maximum power. In this range, efficiency and power are both high; beyond this range, however, there is a large falling off both in efficiency and in power.

An engine is often run at a lower speed than this best range, when such lower speed and power is desirable, despite the lower efficiency; but it is rarely run at much higher speed, on account of increased wear and heating of the engine, as well as decrease in power and efficiency.

The best speed depends upon the design of the engine, — size of ports and bore, length of stroke, mass of moving parts, etc. As a usual thing, airplane engines are designed for a lower speed than automobile engines so as to permit of direct connection to the propeller. Structural and other reasons make high propeller speeds undesirable, the usual speeds being between 1200 and 1600 R.P.M., but speeds beyond this range are not uncommon.

A propeller may be geared down, so as to gain the advantage of high engine speed with low propeller speed, but this gearing adds weight, introduces losses and is an added source of trouble.

Throttle control. — The solid curve for brake horse power in Fig. 44 shows the full power when all adjustments of throttle, ignition and carburetor are made so as to give the greatest possible power at each speed. The pilot controls the power by means of the throttle, less power being obtained by partly closing the throttle.

Dotted curves in the same figure, marked "three-quarters throttle" and "half throttle," show the power obtained by throttling the engine so that, at each speed, the power is three-quarters or one-half the full power at that speed. To obtain precisely the same fraction of full power at each speed would require some adjustment of throttle (with constant throttle, the fractional power being not exactly three-fourths or one-half, or other definite proportion of full power, at all speeds), but this adjustment would not be great. The curves may, therefore, be considered as illustrating the variation of power with speed for various constant throttle positions; they are sufficiently correct for this purpose, although for exact computation they would require some modification. (These dotted curves practically show, also, the decreased power at higher altitudes, for, as discussed later under Altitude, the decrease in air density causes a decrease in power substantially the same as throttling.)

The curves in Fig. 44 are *engine characteristics* and show the power delivered by the engine at different speeds and with different amounts of throttle. Before we can determine how much power is available for flight, we must examine the characteristics of the air propeller.

THE AIR PROPELLER

(a) *Introductory*

The air propeller is mounted on or geared to the engine shaft, — either ahead of the engine as a **tractor**, or behind it as a **pusher**. The propeller is usually constructed with two blades, as in Fig. 45, but not uncommonly it is constructed with four and less commonly with three blades when propeller diameter is limited by the space available. The three-blade propeller is structurally difficult. The requisite strength is most readily obtained with two blades, which pass through the hub as one member.

The forward thrust required to overcome airplane resistance in flight is obtained by the propeller driving back a stream of air in a

so-called **slip-stream**; the greater the backward velocity of this slip-stream and the greater its volume, the greater is the forward reaction or propeller thrust.

In the same way that an upward force or lift is obtained from a moving airfoil because it deflects the air-stream *downward*, a forward force or thrust is obtained from a moving propeller blade because it drives the air-stream *backward*. In each case the force is a reaction obtained by deflecting or driving the air particles in a direction opposite to the force.



FIG. 45. Two-blade propeller.

Although there are various ways of treating the propeller and it is commonly referred to and considered as an air screw, it is most satisfactory to consider the propeller blade — or each element thereof — as an airfoil, with lift and drag determined by its cross-section and angle of attack as for any airfoil. The lift of a propeller blade as an airfoil determines its thrust as a propeller; its drag as an airfoil determines the torque necessary to drive it as a propeller, as discussed more fully later.

Propeller construction. — As mentioned in the preceding paragraph, propellers are usually constructed with two blades. The type of construction of the propeller depends to a large extent upon the materials of which the propeller is made. Propellers were first made of wood, this material still being used for many propellers. The newer materials used for propellers are steel, duralumin, and a composition called micarta.

Wooden propellers are made by gluing together laminations of wood which extend the length of the propeller. After having been given the required shape, these propellers are given a very smooth finish consisting of many coats of water-proof varnish. The advantages claimed for laminated wooden propellers over propellers

made of a single piece of wood are less warping and greater strength. Wooden propellers must be made very thick, especially at the hub where the greatest bending action occurs, to stand up under the loads in flight. For this reason there is a portion of the blade near the hub that is not effective in producing useful thrust.

Metal propellers, because of their greater strength, can be made smaller at the sections near the hub. This results in the metal propeller having more of its length effective in producing thrust than a wooden propeller of the same diameter. The metals used for such propellers are steel and an aluminum alloy called duralumin. The blades, which may be made of either of the above metals, are detachable. These blades are fitted and locked into a steel hub. They may be turned to any desired blade angle, thus making a single propeller suitable for several different airplanes of different powers by a simple adjustment when assembling. The duralumin blades, being lighter than steel and almost equally strong, have gained favor because their use decreases the weight of the rotating parts and therefore the centrifugal forces. Because of the high strength of the metal propeller blades, the blade sections can be made much thinner than those of a wooden propeller for the same operating conditions. This decreases the torque horse power necessary to drive the propeller at any speed without affecting the thrust obtainable with it. This results in metal propellers giving slightly higher efficiencies than wooden propellers designed for the same conditions.⁴

Propellers of micarta are made by the Westinghouse Electric and Manufacturing Company. Micarta is a composition made from layers of specially woven fabric, impregnated with a synthetic bond, and consolidated under high temperature and pressure into a homogeneous mass. The blades are provided with means for adjusting the pitch as with metal propellers. These propellers are said to be quite light and free from flutter and vibration.

⁴ See National Advisory Committee for Aeronautics Technical Reports Nos. 301 and 306, 1929, for comparison of tests made on metal and wooden propellers operating under the same conditions.

advance ratio = ship dimension
 $= \frac{\text{pitch diameter}}{\text{ratio}} = \text{pitch ratio}$
 92 THE AIRPLANE

Screw definitions; pitch and pitch ratio. — Although the action of a propeller is very different from that of a screw, various terms that originated with the screw are applied to the propeller.

When a screw passes through a solid, the distance it moves forward in one revolution is called the **pitch** of the screw. This distance divided by the diameter of the screw is called its **pitch ratio**. The pitch and pitch ratio of a screw may be exactly determined from its dimensions (the distance between threads, and the diameter), the values thus determined being identical with the values determined by actually driving the screw through a solid or turning a bolt in a nut.

The terms pitch and pitch ratio are applied to a propeller as to a screw. It is found, however, that the **effective pitch** ⁵ p_e , of a propeller — the distance the propeller moves forward through the air in one revolution — is not the same as its **geometrical pitch** determined from its dimensions as a screw passing through a solid.

The mean of the geometrical pitches of the several propeller elements is called the **mean geometrical pitch**.

In propeller operation it is its effective pitch, rather than its geometrical pitch, in which we are most interested. As shown later, the effective pitch of a propeller varies with conditions of operation, being sometimes less and sometimes more than the geometrical pitch which has but one value fixed by its dimensions.

Definitions of torque horse power, thrust horse power and efficiency. — The power available for propelling an airplane through the air comes directly from the propeller thrust, the amount of power thus furnished, as already pointed out, being proportional to the product of propeller thrust and airplane velocity. The propeller itself, however, does not create this power; it merely *transmits* power that it receives from the engine, the power it thus receives being proportional to the product of the torque ⁶ in the

⁵ Called also "experimental pitch."

⁶ Torque is a turning moment equal to the product Fr of a force F and the perpendicular distance r from the axis of rotation to the line of action of the force. If F is in pounds and r in feet, torque horse power is $2\pi NFr / 33000$, for one horse power is 33000 ft. lbs. per min.

propeller shaft and its speed in revolutions per minute. The speed of the propeller is the speed of the engine, unless reduced by gearing. "Speed," here and elsewhere in this discussion, refers to speed of rotation, often referred to as "revs." or R.P.M., and not to the forward translation referred to as "velocity" or "miles per hour."

Of the three elements for flight, — engine, propeller and airplane, — the propeller is thus seen to be the intermediary or "middle-man," receiving power from the engine and delivering this power in a form available for propelling the airplane. The power the propeller receives is **torque horse power** and this is the brake horse power of the engine already discussed. The power the propeller delivers is **thrust horse power** and this is the power available for airplane propulsion.

The **efficiency** of a propeller is the ratio of thrust horse power to torque horse power. The entire output of the engine would thus be available as thrust horse power for propelling the airplane, if the efficiency of the propeller were 100 per cent. On account of losses, however, the efficiency of a propeller is less than 100 per cent., so that not all of the engine output is thus available. Under best conditions, the efficiency of a propeller may be 80 or 85 per cent., but under working conditions it is usually less; thus, when the brake horse power of the engine is 100, perhaps only 60 or 70 horse power may be available for propeller thrust.

The air propeller, working in a compressible medium, is more efficient than the marine propeller working in a medium that is practically incompressible. The rarefaction and compression before and behind the blade of a propeller in air — as above and below an airfoil — are factors not found in water. (In water, when a negative pressure created by the relative motion of blade and water exceeds the static pressure of the water, it is not possible for the water to become rarefied but a discontinuous flow occurs known as *cavitation*. To avoid this, the blades of a marine propeller are made short and wide, and not long and narrow as in an air propeller.)

A knowledge of how power ⁷ and efficiency are affected by different conditions of operation is most essential for the understanding of the propeller. Fortunately these relations, so far as results in operation are concerned are simple.

Let us first see what are the varying conditions of propeller operation. We shall then see what are the characteristics of a propeller under these different conditions of operation, after which we will consider the theory of the propeller that accounts for these characteristics.

(b) Conditions of Propeller Operation

V and N , the two variables in propeller operation. — During flight the two variables in propeller operation upon which other quantities depend are its forward velocity V and its speed or revolutions per minute N . (The effect of a third variable, the change of air density with altitude, is left for a later discussion.) The dimensions and shape of the propeller itself can only be changed by a change of propeller when not in flight.⁸

It will be found that propeller characteristics depend not only upon the absolute values of V and N but upon their relative values as well. The ratio of V to N , and the ratio V/ND , where D is propeller diameter, have special significance.

The values of V and N are known to the pilot by his air-speed meter and his revolution indicator. They are, furthermore, quantities that he directly controls. For these reasons, propeller characteristics are better understood — by a pilot at least — when expressed in terms of V and N than when expressed in terms of effective pitch, angle of blade attack or slip, quantities that are only indirectly known and controlled by the pilot. It is well, however,

⁷ Power is of first importance. It makes little difference how efficient a propeller is, if it does not have enough power to do its intended work. A small desk fan, even were it 100 per cent. efficient, would not serve for propelling an airplane so well as a propeller with adequate power having an efficiency of only 50 per cent. Adequate power being assured, conditions of operation that give high efficiency should be sought.

⁸ Adjustable propellers, in which the pitch can be changed during flight, have been used but have not been widely introduced.

to be able to interpret propeller characteristics when expressed in these various terms, for each has its significance; effective pitch and slip are convenient terms in the comparison of propellers of different diameter, while the angle of attack the blade makes with the air is useful in propeller theory, as discussed later.

V/N , the forward travel per revolution or effective pitch. — When a propeller making N revolutions per minute, is moving forward with a velocity of V ft. per minute, the distance that the propeller moves forward in one revolution is seen to be V/N feet. This distance, in feet or other unit of length, is called the **effective pitch** of the propeller; it varies with the relative values of V and N , under different conditions of operation, but is independent of their absolute values. (Thus, when $V = 5000$ ft. per min. and $N = 1000$ R.P.M. the propeller moves forward in one revolution a distance $V/N = 5$ ft., which is the effective pitch of the propeller; when $V = 6000$ and $N = 1200$, the effective pitch V/N is still equal to 5 ft.)

V/ND , the ratio of forward travel per revolution to diameter. — This forward travel per revolution, when expressed in terms of propeller diameter D (instead of in feet) is V/ND and is called the **effective pitch ratio or the slip function**. Thus, in the preceding example, if the propeller has a diameter of 8 feet, $V/ND = 5 \div 8 = 0.625$, which is the effective pitch ratio of the propeller and means that in each revolution the propeller travels forward a distance 0.625 times its diameter. V/ND is a number, independent of units; the units used, however, must be consistent.⁹

The value of V/ND indicates, to a certain extent, the conditions of propeller operation. Being independent of units, it is more use-

⁹ If N is expressed in R.P.M. and D in feet, V must be expressed in ft. per minute. For example, an 8 ft. propeller makes 1200 R.P.M. When $V/ND = 0.5$, $V = 0.5 \times 1200 \times 8 = 4800$ ft. per min. (54.5 MPH); when $V/ND = 1$, $V = 9600$ ft. per min. (109 MPH.). The value of V/ND is frequently in this range (0.5 to 1.0), but these values are given for illustration and not as limits.

If N were revolutions per sec. and D meters, V must be meters per second; V/ND would be unchanged, being independent of units.

ful for this purpose than V/N . Various propeller quantities (for example, efficiency, Figs. 55 and 56) are accordingly plotted in terms of V/ND .

Since the peripheral velocity of a propeller is πND , it is seen that V/ND is proportional to the ratio of the forward velocity to the peripheral velocity of the propeller tip.

Zero-thrust pitch and pitch ratio. — The effective pitch, or forward travel of a propeller per revolution, as just stated, varies under different conditions of operation. It will be shown later that, as effective pitch increases, thrust decreases and finally becomes zero. The propeller then goes through the air smoothly, as a screw with no slip, without imparting velocity to the air particles.

The particular value of effective pitch that gives zero thrust is called the **zero-thrust pitch** of the propeller. It is characteristic of each propeller and like a dimension (expressed in feet or other unit of length) cannot be changed.

The **zero-thrust pitch ratio** is the ratio of the zero-thrust pitch to the propeller diameter D , and is a number independent of units. Otherwise defined, it is the value of V/ND when there is no thrust and no slip.

As an illustration, if a 10 ft. propeller creates no thrust when its forward travel per revolution is $V/N = 9$ ft., the zero-thrust pitch ratio is $V/ND = 9 \div 10 = 0.9$. This is a constant of the propeller and is the same whether V and N be large or small. Practical values for zero-thrust pitch ratio are between 0.5 and 1.5.

Slip. — Positive thrust is obtained only when the forward travel per revolution, or the effective pitch, is *less*¹⁰ than the zero-thrust pitch. The difference between the mean geometrical pitch and the effective pitch, expressed as a percentage of the former, is called

¹⁰ When the travel is greater than the zero-thrust pitch and the slip is negative (as in diving) a negative thrust is developed, the propeller then acting as a brake; see Fig. 51.

the **slip**. Thus, when a propeller with a mean geometrical pitch of 8 feet travels forward only 6 feet in one revolution, the slip is 25 per cent., or .25. *An older definition of slip is the difference between the zero-thrust pitch and the effective pitch.* This older definition was used in making Figs. 51 to 56, inclusive.

When the slip is 100 s per cent., the forward travel per revolution is

$$V/N = \text{effective pitch} = (1 - s) \text{ mean geometrical pitch.}$$

As a ratio in terms of D , we have accordingly

$$\begin{aligned} V/ND &= \text{effective pitch ratio} \\ &= (1 - s) \text{ mean geometrical pitch ratio.} \end{aligned}$$

It is seen that when the slip is zero, the effective pitch becomes equal to the mean geometrical pitch. By the older definition the effective pitch equals the zero-thrust pitch for zero slip.

Zero-thrust pitch greater than geometric pitch. — The zero-thrust pitch and pitch ratio of a propeller are greater ¹¹ than the geometric pitch and pitch ratio. In other words, the actual forward travel of a propeller through the air for no thrust is greater than its travel calculated as a screw passing through a solid, unyielding material. It is for this reason that the screw theory of the propeller is abandoned.

The explanation lies in the fact that the air through which the propeller is passing is a compressible gas and not an unyielding solid. The propeller blade in cutting through the air acts not as a screw but as an airfoil — as discussed later under propeller theory — and, like any airfoil, gives rise to a rarefaction ¹² on its upper surface (in front of the propeller) and a condensation on the lower surface (back of propeller). Calculations for a propeller as a screw take no account of this rarefaction and condensation of the air and for this reason calculated or geometric values for pitch and

¹¹ Forty-eight propellers discussed by Durand in Report No. 14, referred to later, have values of zero-thrust pitch between 1.17 and 1.54 times the geometrical pitch.

¹² See Fig. 86.

pitch ratio always differ from the actual zero-thrust values. The result in flight is much the same as though the whole body of air immediately surrounding a propeller were being carried forward with it, so that more than the calculated velocity is necessary in order to get zero thrust and this may serve as a rough explanation.

Zero-thrust pitch and pitch ratio can only be determined by experiment, where special facilities are available, whereas geometrical pitch and pitch ratio can be determined by measurements described later on the propeller itself. For this reason the values for pitch and pitch ratio usually given are *nominal values*, and are always so understood *unless otherwise specified*. The **nominal** or **standard pitch** of a propeller is the geometrical pitch taken at two-thirds of the propeller radius.

The relation between V and N and the significance of slip, pitch and pitch ratio in propeller operation will be brought out more fully in the subsequent discussion of propeller characteristics and propeller theory.



(c) *Propeller Characteristics*

The behavior of a propeller under various conditions of operation will be understood by examining the characteristic curves that follow. These are working results, independent of any theory, the performance of the propeller being to many readers of first importance. A discussion of theory will follow, but some may prefer to read the theory before examining the performance.

The conditions of operation depend upon the relation between V and N , and this in turn requires first a study of torque horse power. Other characteristics will be studied in turn.

Torque horse power for different values of N and V . — The torque horse power required to drive a given propeller varies both with its speed N (revolutions per minute) and the forward velocity V (miles per hour) at which it is moving through the air.

For any constant value of V , torque horse power increases as the revolutions per minute increase; in other words, it is found,

as might be supposed, that more power is required to turn a propeller fast than to turn it slowly. This is shown by the curves in Fig. 46 for the torque horse power of a particular¹³ propeller at three different velocities, 50, 100 and 150 miles per hour. By comparing these curves it is seen that torque horse power is less for high than for low velocities.

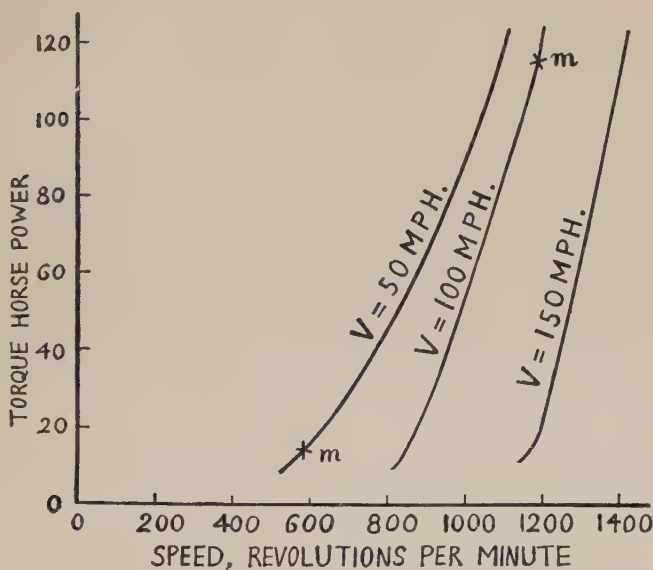


FIG. 46. Torque horse power required to drive a particular propeller at different speeds (revolutions per minute) when travelling through the air at 50, 100 and 150 MPH., at ground level. Propeller diameter, 8'9" pitch ratio, 0.9. Maximum propeller efficiency is at *m*.

The decrease in torque horse power as V increases is better shown by the curves in Fig. 47 in which N is constant and V is variable. It takes less power to drive a propeller, at any given

¹³ The curves in Figs. 46 (and subsequent curves, unless otherwise stated) relate to a propeller 8'9" in diameter, with geometrical pitch ratio 0.9. The curves have been plotted from calculations based upon experimental data for Propeller No. 3, as given by W. F. Durand in Report No. 14, National Advisory Committee for Aeronautics, 1917. All curves relate to ground level, air density = 0.0789, lbs. per cu. ft. The point *m* on any curve is the point of maximum propeller efficiency.

number of revolutions per minute, when the propeller has a forward velocity V than when it is stationary. Propeller thrust, as discussed later, is a maximum when the propeller is stationary; torque, also, is then a maximum, as well as torque horse power as shown by the curves.

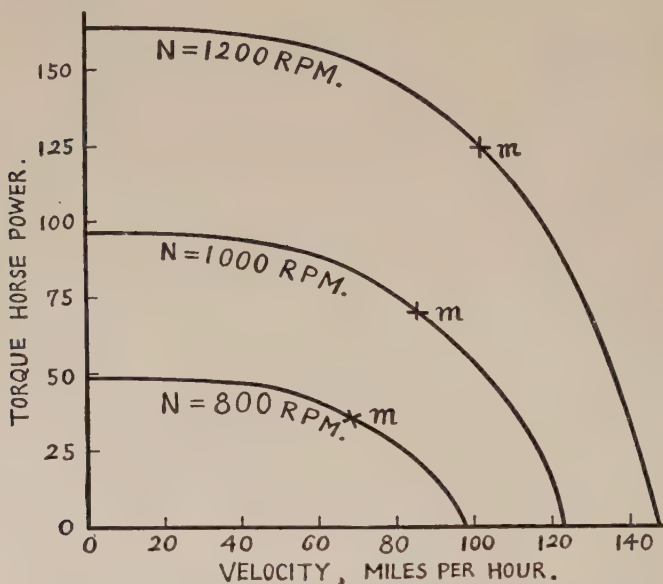


FIG. 47. Variation of propeller torque horse power with velocity when propeller is driven at constant speed. Same data as Fig. 46. Maximum efficiency at m .

As V increases, torque horse power continues to decrease and becomes zero when a certain velocity is reached. At higher velocities, torque horse power is negative; the propeller, instead of receiving power from the engine, then *drives the engine*, receiving power as an air motor from the air. This means that the airplane is descending in a glide or dive and that power is supplied by gravity. The airplane is being retarded by the propeller as by a brake. With V constant, as in Fig. 46, torque horse power is negative when N is less than a certain value; the negative values of torque horse power are not shown in the curves.

Torque horse power is an important element in determining the relation between N and V .

Relation between N and V . — The velocity V of an airplane in flight is determined by its angle of attack, as discussed in Chapter II, and is controlled entirely by the elevator. *The revolutions per minute or speed N , although controlled by the throttle, depend not only upon engine throttle but also upon airplane velocity V .* Let us see in what way the speed N is determined.

For any given velocity, for example $V = 100$ MPH., we have a curve, as in Fig. 46, showing torque horse power for each value of speed N . But torque horse power received by the propeller must equal brake horse power delivered by the engine. The engine and propeller, accordingly, speed up until a speed N is reached at which the propeller absorbs all the power output of the engine, that is, they speed up until torque horse power of the propeller and brake horse power of the engine are exactly equal.

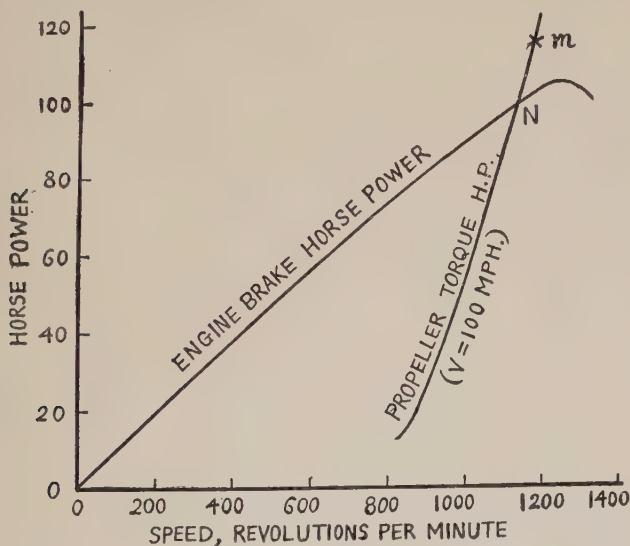


FIG. 48. Speed N and power, of particular engine and propeller, determined by intersection of curves for engine brake horse power and propeller torque horse power.

This is made clear in Fig. 48, which shows a curve for engine brake horse power for a particular amount of throttle (reproduced from Fig. 44 with full throttle) and a curve for propeller torque horse power for a particular velocity (reproduced from Fig. 46 for $V = 100$ MPH.) The intersection¹⁴ of these two curves determines the speed N and also the power, for the particular value of V and particular amount of throttle. The intersection will be shifted as either curve is shifted by control of throttle or change of V ; or, both curves may be shifted simultaneously with a sort of scissors motion.

Value of N for different amounts of throttle.—The control of

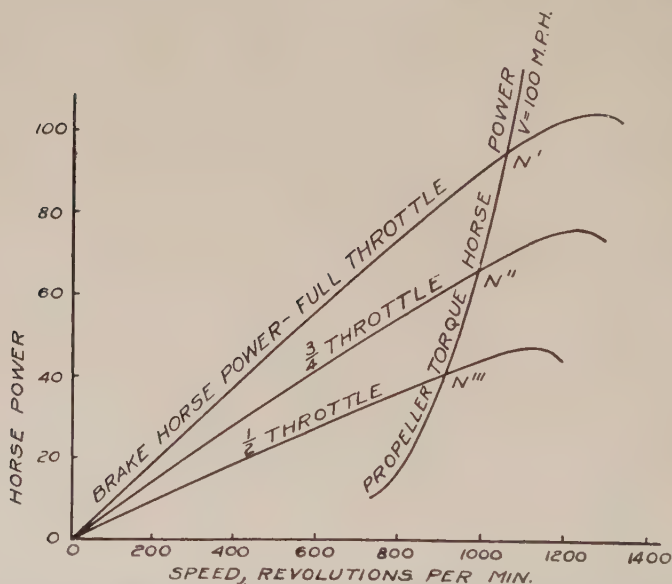


FIG. 49. Speed N' , N'' and N''' and corresponding power, for particular engine and propeller, determined for three different amounts of engine throttle, when velocity is 100 MPH.

¹⁴ Curves may be drawn for engine and propeller torque, instead of engine and propeller power, determining N by their intersection in the same manner. Curves for propeller torque, at different speeds N , are continuously rising curves, somewhat like the curves for torque horse power in Fig. 46. Curves for engine torque at different speeds are nearly horizontal, through a certain range of speed, dropping sharply at higher speeds.

engine speed and power by throttle, for one value of V , is shown in Fig. 49. As the throttle is changed from "full throttle" to " $\frac{3}{4}$ throttle" and " $\frac{1}{2}$ throttle," the intersection is changed from N' to N'' and N''' , with corresponding change in engine speed and power.

Value of N for different values of V .—The change of engine speed and power for several different values of V , is shown in the same manner in Fig. 50. The speed and power corresponding to velocities of 50, 75, 100, 125 and 150 MPH., are determined for "full throttle," " $\frac{3}{4}$ throttle" or " $\frac{1}{2}$ throttle," by the several intersections.

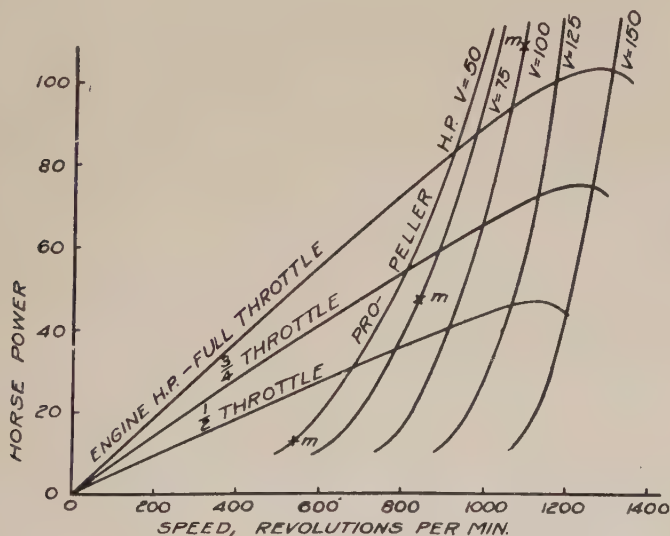


FIG. 50. Curves for engine brake horse power for different amounts of throttle and propeller torque horse power for different velocities. Intersections determine speed and power for each velocity and amount of throttle. Maximum efficiency at m .

It is seen that the speed N of engine and propeller depends not only upon engine throttle (which is directly controlled by the pilot), but also upon airplane velocity, which is indirectly controlled by the pilot by means of the elevator. For constant throttle, there is a

definite speed N corresponding to each velocity V ; and for constant velocity, there is a definite speed N for each position of the throttle.

The curves shown, Figs. 48, 49 and 50, relate to a particular propeller and engine; for other engines and propellers the general nature of the results would be the same, although numerical results would differ.

Thrust horse power at varying velocities. — A consideration of the thrust horse power delivered by a propeller under different conditions of operation is obviously of utmost importance, the sole purpose of a propeller being to produce thrust and thrust power. Like other propeller quantities these both vary as N and V are varied. It is, however, most satisfactory to plot their values for varying values of V , so that direct comparison can be made between curves for thrust power (power available) and curves for airplane power required, which are plotted in terms of V .

Before discussing thrust power, let us consider propeller thrust upon which thrust power depends.

Propeller thrust. — Thrust depends upon the backward velocity imparted to the air by the propeller, that is, the backward velocity of the slip stream *with respect to the surrounding stationary air*. The thrust developed by a propeller will, accordingly, vary with the forward velocity V of the propeller and will be a maximum when V is zero, namely, when the airplane is stationary, for the velocity of the slip stream, with respect to the surrounding air, is then a maximum. The thrust, when the airplane is stationary, is called the **static thrust**.

When the propeller is moving forward with a velocity V , the backward velocity of the slip stream is less with respect to the surrounding stationary air and the thrust is accordingly less.

Thrust decreases as V increases, as shown in Fig. 51.

Thrust continues to decrease as V increases, and finally thrust becomes zero when the propeller has a forward velocity V just equal to the backward velocity of the slip stream relative to the propeller. The velocity of the slip stream, with respect to the

stationary air, is then zero and no thrust is created, for no velocity has been imparted to the air by the propeller. Slip is then zero according to the older definition.

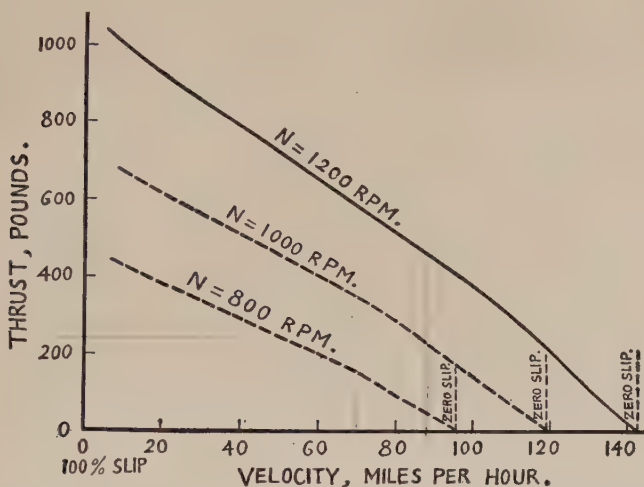


FIG. 51. Variation of thrust with velocity, for a particular propeller, when driven at constant speed. Pitch ratio 0.9, diameter 8' 9". The slip indicated is according to the old definition.

The solid curve in Fig. 51 shows the variation of thrust with velocity for a particular propeller when driven at 1200 R.P.M. The dotted curves show the thrust at 1000 and 800 R.P.M. In all cases 100 per cent. slip corresponds to zero velocity; zero slip, by the older definition, corresponds to zero thrust.

Thrust horse power derived from thrust. — Thrust horse power is readily derived from thrust, being equal to the product of thrust and velocity, divided by 375 when thrust is in pounds and velocity is in miles per hour.

Fig. 52 shows curves for thrust and velocity, and a curve for thrust power thus obtained from their product. It is seen that thrust power is zero when $V = 0$, at 100 per cent. slip; thrust is then a maximum. It is seen, also, that thrust power is zero when thrust is zero, at zero slip (older definition); V then has a certain

definite value. These curves are drawn for a constant speed, $N = 1200$ R.P.M.

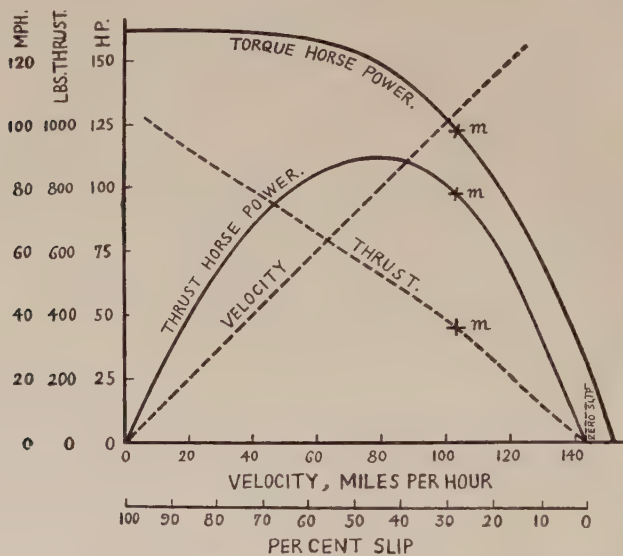


FIG. 52. Variation of thrust horse power with velocity for a particular propeller when driven at 1200 R.P.M. Dotted curves show thrust and velocity, thrust power being obtained by multiplying thrust and velocity (The straight line for velocity might be omitted as it furnishes no additional information.) The upper curve, reproduced from Fig. 47, shows torque horse power for comparison. The slip indicated is according to the old definition.

A curve for torque horse power, reproduced from Fig. 47, is shown in Fig. 52 for comparison; this makes possible a determination of efficiency, discussed later.

For the curves shown in Fig. 52, maximum thrust power is obtained when the slip is 44 per cent.; maximum efficiency, at the point *m*, when the slip is 28.7 per cent.

Thrust horse power for different values of speed N . — The curves in Fig. 53 show the variation of thrust horse power with velocity for a propeller driven at different speeds N . They strikingly show that, for each speed, there is a certain velocity at which

the power is a maximum, and that the value of this maximum is greater for greater values of speed N .

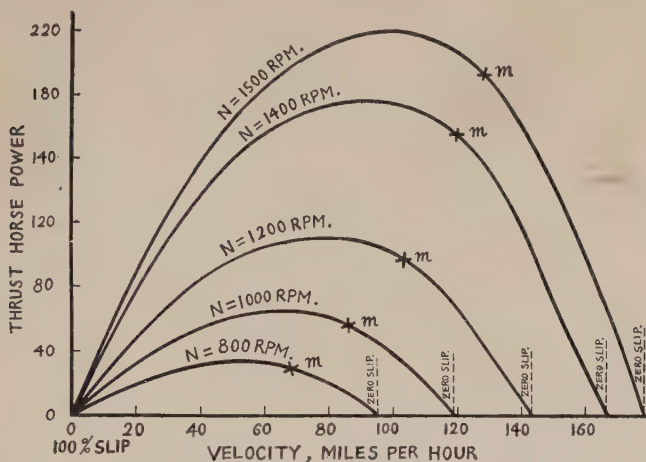


FIG. 53. Curves for thrust horse power (usually called power available) for particular propeller driven at different speeds N , by any engine. Maximum propeller efficiency is at m . The slip indicated is according to the old definition.

These are the so-called curves for **power available** which — when compared with the curves for power required — have an important bearing upon power relations in flight. They are the most useful of propeller curves and should be carefully studied so that a picture of them may be kept in mind. Although plotted for a particular propeller, they are typical of the curves for power available for any propeller. They are independent of the motor used, for *any* motor (not necessarily a gas engine) may be used provided it has sufficient power to drive the propeller. (Curves for propeller thrust horse power, when a particular engine is used, are shown later in Fig. 57.)

A propeller delivers its maximum power when the slip is, say, 40 to 50 per cent. (in this case about 45 per cent.); it has its maximum efficiency — discussed in a later paragraph — when the slip is, say, 25 to 40 per cent. (in this case about 30 per cent.). There is considerable variation in these values with different propellers,

but maximum power always occurs at a greater slip than maximum efficiency. *The best range for propeller operation is between the point for maximum power and the point for maximum efficiency.*

Thrust horse power for propellers of different diameters D . —

Greater thrust horse power can be obtained by increasing N as just shown, but is often better obtained by using a propeller of larger diameter D , the greater power in this case being due to the

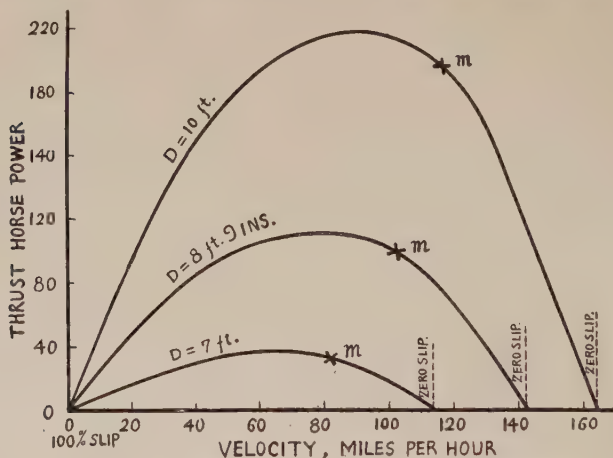


FIG. 54. Thrust horse power of similar propellers with different diameters, at constant speed $N = 1200$ R.P.M. Pitch ratio 0.9. Maximum efficiency at m . The slip indicated is according to the old definition.

greater volume of the air-stream. The curves in Fig. 54 show the power obtained, at different velocities, from propellers of different diameters when driven at the same speed.

An airplane should be designed for as large a propeller as space permits, for a large propeller at moderate speed is (generally speaking) better than a smaller propeller at very high speed; but the larger propeller is objectionable if it necessitates an undue elevation of the center of gravity of the airplane. On account of this limitation and the necessity of having sufficient clearance between the propeller and the ground, the huge propellers satisfactorily used on airships are not used on airplanes. A clearance between the pro-

pellor and ground, as little as 10 inches has been found sufficient in some types of planes.

Assured of sufficient thrust power delivered by the propeller, we next inquire as to the efficiency of the propeller under different conditions of operation.

Propeller efficiency for different values of V/ND . — The efficiency of a propeller is equal to thrust horse power delivered divided by torque horse power received. Note the curves for torque power and thrust power in Fig. 52; a comparison of these is very interesting.

It has been found that efficiency depends upon the ratio V/N and not upon the absolute values of V or N ; if V and N are both changed in the same proportion, efficiency remains unchanged. Furthermore, in comparing propellers of the same design but with different diameters D , it is found that efficiency depends not upon V/N but upon V/ND , namely, the effective pitch ratio which varies with the slip. Propeller efficiencies are, therefore, plotted for various values of V/ND or for various values of slip. Both scales are shown in Fig. 55.

Referring to Fig. 55, and to Fig. 52 which relates to the same propeller, it is seen that when $V/ND = 0$, corresponding to 100 per cent. slip, thrust power is zero and hence propeller efficiency is zero. As V/ND increases, propeller efficiency increases until a maximum efficiency of 80 per cent., or so, is reached. As V/ND is further increased, the efficiency decreases, and again becomes zero when V/ND reaches a certain value (the zero-thrust pitch ratio of the propeller) corresponding to zero thrust and zero slip by the older definition. It is seen, from Fig. 55, that this propeller has a zero-thrust pitch ratio 1.2, whereas the geometrical pitch ratio is 0.9.

Every propeller has an efficiency curve of the type shown in Fig. 55. It is seen that for a given number of revolutions per minute there is a certain airplane velocity V , or for a given airplane velocity V there is a certain number of propeller revolutions N , at which the efficiency of a particular propeller is a maximum.

A propeller should, accordingly, be selected ¹⁵ that has high efficiency and power at the operating values of V and N . A propeller

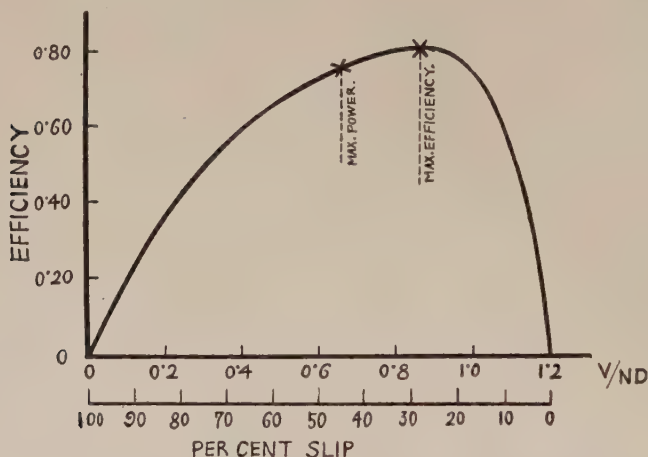


FIG. 55. Propeller efficiency for different values of V/ND . Efficiency is equal to thrust horse power divided by torque horse power; see Fig. 52. Pitch ratio, 0.9. Values for V , N or D are not fixed. Zero-thrust pitch ratio, 1.2. The slip indicated is according to the old definitions.

that is very good for a certain airplane and engine may be very poor for another airplane or engine. In other words, the propeller, engine and plane *must fit*, so that each will be operating under good conditions.

It is well to operate a propeller at a value of V/ND somewhat lower (rather than higher) than the value of maximum efficiency, in order to obtain greater power. The points for maximum power ¹⁶ and maximum efficiency are marked on the curve. As already stated, maximum efficiency occurs when the slip is, say, 25 to 40

¹⁵ The same care in selection has to be taken in case of a marine propeller. Take as an illustration two tug boats, with identical hulls and engines, but different propellers. One boat, with propeller that gives full power when travelling at high velocity, far outstrips the other in the race to an incoming steamer, but when it comes to pulling a load it is inferior to the other boat equipped with a propeller that gives full power when travelling at low velocity.

¹⁶ The point for maximum power depends upon D and pitch ratio. The point is marked here for $D = 8' 9''$ and pitch ratio = 0.9.

per cent., and maximum power when the slip is, say, 40 to 50 per cent.

A *wide range* of high efficiency is usually more desirable than a narrower range of slightly higher efficiency.

Pitch ratio and efficiency. — The efficiency curves for three propellers with different pitch ratios but otherwise similar are shown in Fig. 56. The geometrical pitch ratios of the three propellers are 0.5, 0.7, and 0.9; the zero-thrust pitch ratios (shown by the values

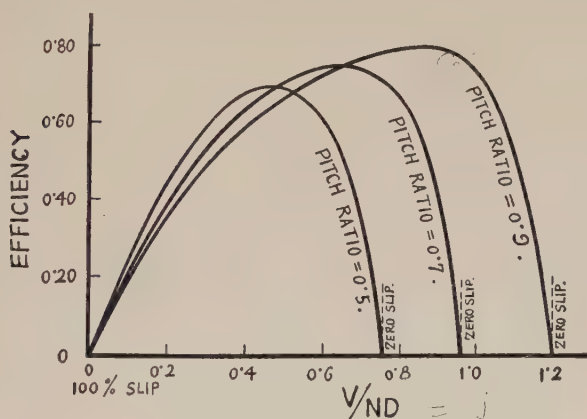


FIG. 56. Efficiency of three similar propellers with different geometrical pitch ratios. Zero-thrust pitch ratio, shown by points of zero slip are 0.76, 0.96 and 1.2. The slip indicated is according to the old definition.

of V/ND when the efficiency curves fall to zero) are 0.76, 0.96 and 1.2, respectively. Which propeller is the best to use is seen to depend upon what the value of V/ND is under working conditions. Thus, when V/ND is less than 0.47, the propeller with pitch ratio 0.5 is seen to be the most efficient of the three; when V/ND is more than 0.52, this same propeller is the least efficient.

Pitch ratio and power. — Pitch ratio does not affect efficiency alone. In Fig. 57 are shown curves of thrust power for the same three propellers, having geometrical pitch ratios 0.5, 0.7 and 0.9. It is seen that for maximum power, as well as for maximum effi-

ciency, the value of V/ND must be greater for the propeller of greater pitch. For the three propellers here shown, maximum power is seen to increase with pitch ratio, but this is true only for a limited range of pitch ratio.

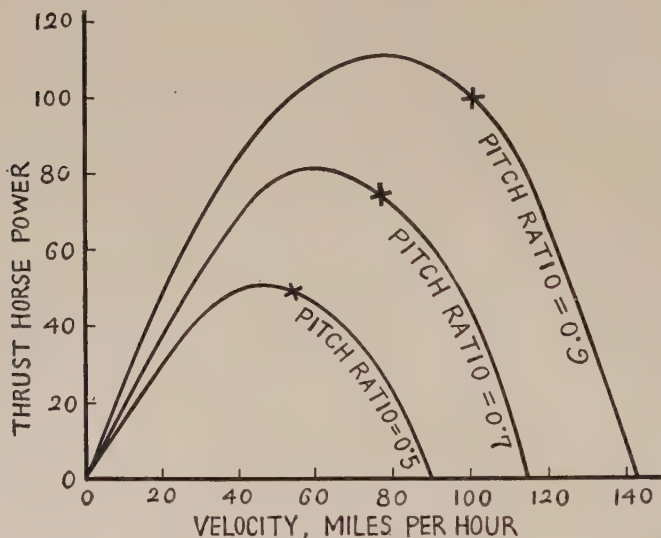


FIG. 57. Thrust horse power of three similar propellers with different pitch ratios. Point of maximum efficiency is marked by x.

Combined engine and propeller characteristics. — We have discussed various propeller characteristics independent of the motor used to drive the propeller, the separate study of engine and propeller being for most purposes preferable. Thus, in Fig. 53 was shown the thrust horse power obtained from a certain propeller driven at specified constant speeds by any motor. This constant speed is obtained by throttle adjustment, when a gas engine is used.

In Fig. 58 are shown curves for thrust horse power for a given propeller driven by a particular gas engine, these curves being not for constant speed as in Fig. 53, but for constant throttle.

It was shown in Fig. 50 how the brake horse power and speed N are determined for full throttle (or for $\frac{3}{4}$ or $\frac{1}{2}$ throttle) when V is 50, 75, 100, 125 or 150 MPH. Thrust horse power may be

obtained by multiplying brake horse power, as here shown, by efficiency, which is known from Fig. 55 when V , N and D are shown. The curves in Fig. 58 were thus determined.

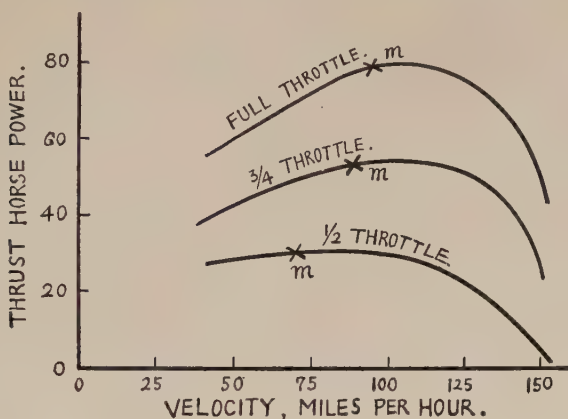


FIG. 58. Combined engine and propeller characteristic. Thrust horse power, or power available, for constant throttle; a particular propeller (pitch ratio 0.9, diameter 8' 9") driven by a particular engine. Maximum efficiency at m . For engine curves, see Fig. 44.

The chief propeller characteristics have now been shown, most important being the curves of power available in Fig. 53, useful for direct comparison with curves of power required.

Let us now examine briefly the basis for propeller theory.



(d) Propeller Theory

The foregoing discussion of the characteristics of a propeller in operation shows working results in simple form; these are the facts that can be easily understood, independent of any theory that may be used to explain them.

The oldest theory of the propeller treats it as a screw, which moves forward as it turns, and upon this conception are based many propeller terms in common use. In an incompressible fluid, as water, the screw theory is fairly satisfactory and the marine propeller is, accordingly, commonly treated as a screw.

When, however, the medium is air, which can be compressed and rarefied as any gas and has a density only $1/800$ the density of water, the screw theory is far from satisfactory and, as a theory for the air propeller, has been practically abandoned.

Airfoil theory of the propeller. — The most satisfactory theory of the air propeller, developed by Drzewiecki, considers the propeller blade as a rotating airfoil. When the propeller is merely rotating and has no forward velocity, each element of the blade moves in a circle, the plane of rotation being perpendicular to the propeller shaft. When the propeller makes N revolutions per minute, the velocity of rotation of any element at a distance r feet from the center of the shaft is $2\pi r N$ feet per minute.

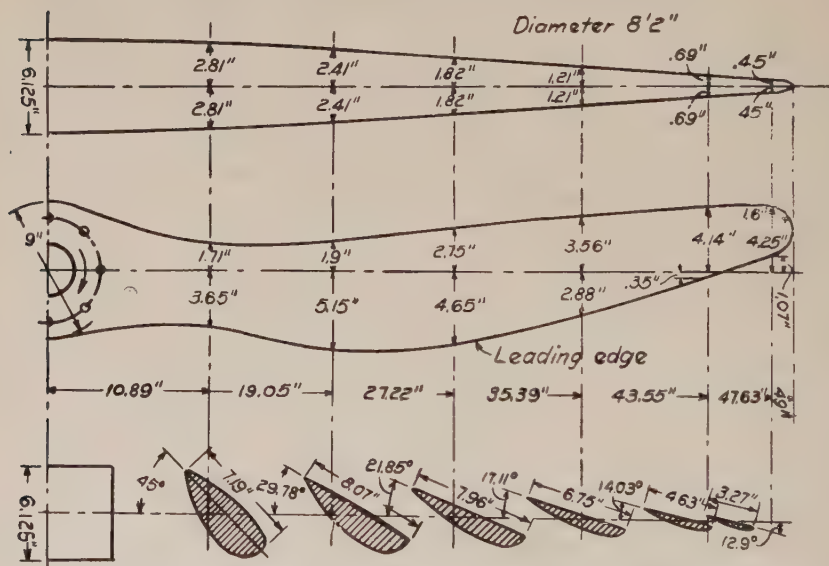


FIG 59. Plan of propeller blade (viewed in direction of shaft) and sections of blade at various distances r from the center of shaft. Note that as r increases the blade angle decreases.

In flight the propeller has a forward velocity in addition to its rotation, and the path of any element is a cork-screw curve or helix and not a circle. The velocity of any element along this path is

then the resultant of its forward velocity V and its velocity of rotation, $2\pi r N$, as shown later in Fig. 62.

Fig. 59 shows the plan of a propeller blade and several sections at different distances from the center. The similarity of these sections to the section of an airplane wing and the justification of the airfoil theory is obvious.

Fig. 60 is an illustrative diagram (not to scale) of one section of a propeller blade, viewed radially, developing more fully the airfoil theory. Fig. 61 shows this section in relation to the propeller shaft. Each section or "element" of the blade may thus be treated as an airfoil.

The **blade angle** (geometrical pitch angle) for any particular section is the angle a between its chord and the direction of its rotation in a plane perpendicular to the propeller shaft. As shown

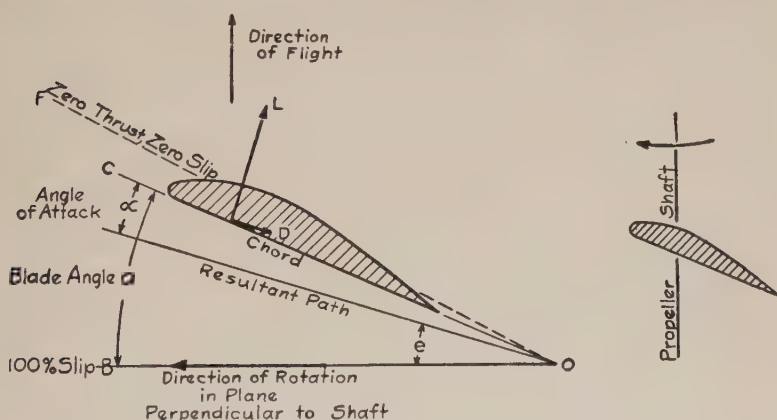


FIG. 60. Particular section of propeller blade (viewed in a radial direction) at distance of r from center of shaft, showing the behavior of a propeller blade as an airfoil, attacking the air at an angle of attack α . The angle e is the effective pitch angle.

in Fig. 59, this angle decreases for the various sections of a blade as we proceed from hub or boss to tip; that is, the blade angle a decreases¹⁷ as the distance r from the hub increases.

¹⁷ *Determination of pitch from propeller measurement.* — The tangent of a is equal to the geometrical pitch divided by $2\pi r$. The geometrical pitch of a propeller is, accordingly, equal to $2\pi r \tan a$ and can be determined by measuring the pitch angle at any distance r from the hub.

The **angle of attack**, α , at which any blade element or section attacks the relative air due to its motion, is the angle between the

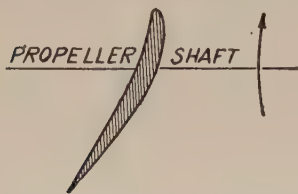


FIG. 61. Relation of section of propeller blade to propeller shaft; radial view.

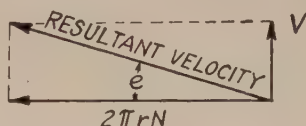


FIG. 62. Resultant velocity is the resultant of the velocity of flight V , and the velocity of rotation $2\pi r N$. The angle e is the effective pitch angle.

chord of the element and its resultant flight path, as shown in Fig. 60.

When a propeller is rotating, but has no forward velocity, its motion is in the plane of rotation and the velocity of any particular blade element is $2\pi r N$; the angle of attack of a blade element is now equal to the pitch angle a .

In flight, when there is a forward velocity V , the resultant motion or flight of a blade element is a helix and the resultant velocity of the blade element is the resultant of its forward velocity V , and its velocity of rotation $2\pi r N$, as shown in Fig. 62.¹⁸

The **effective pitch angle**, as shown in Figs. 60 and 62, is the angle e which the resultant flight path makes with the plane of rotation. The effective pitch angle varies with different conditions of operation and increases as V/N increases, the tangent of e being equal to $V/2\pi r N$. The effective pitch angle thus determines the forward travel of the propeller per revolution.

As already stated, the angle of attack of a blade element with

The geometrical pitch ratio p is $\pi \tan a$, being equal to the geometrical pitch divided by 2π . We have, likewise, $\tan a = p/\pi$.

¹⁸ Experimentation by Mr. F. W. Caldwell has shown that the effective forward velocity is greater than V by the velocity which the air has just before it encounters the propeller. Thus the effective forward velocity is $V + v$, where v is the "in-draft velocity." Mr. Caldwell has shown that the in-draft velocity may be taken equal to one-half the difference between the speed of the slip-stream and the speed of the airplane. Applying this correction would cause a slight increase in the angle e in Figs. 60 and 62.

the relative wind is the angle α between its chord and the resultant flight path. OP , in Fig. 60, shows a short portion of this path. It will be seen that as the forward velocity V increases (relative to N) the angle of blade attack decreases.

The effective pitch angle and effective pitch are zero when $V = 0$, corresponding to 100 per cent. slip and maximum thrust; the angle of blade attack is then a maximum and the thrust is a maximum.

Lift and drag. — As in the case of any airfoil, each blade element has a lift perpendicular to, and a drag or resistance in the direction of, the flight path. The direction of L and D are indicated in Fig. 60. Their values are

$$\begin{aligned}\text{Lift} &= L = K_L S V_R^2; \\ \text{Drag} &= D = K_D S V_R^2.\end{aligned}$$

Here S is the area of the blade element; V_R its resultant velocity along its helical path; K_L and K_D are the usual coefficients which depend upon airfoil shape and vary with the angle of blade attack.

Thrust and torque. — The component of force parallel to the shaft of the propeller gives **thrust**; the component of force in the direction of rotation gives **torque**. Although thrust results from lift, it is seen that thrust is not precisely equal to lift; nor is torque precisely equal to drag.

The total thrust and torque for the propeller as a whole is the sum of the thrust and torque of the separate blade elements.

Angle of blade attack. — The angle of attack α varies during flight from, say, 2° or 3° in horizontal flight to, say, 10° or perhaps 12° in climbing. As the angle of attack increases (with an increase in slip and decrease in V/N) the lift, and so the thrust,¹⁹ increases. The increase in thrust, with increase in slip and decrease in V/N ,

¹⁹ Thrust is equal to the component of L parallel to the shaft, less the component of D in that direction. Torque is the sum of the components of L and D in the plane of rotation. Thus,

$$\begin{aligned}\text{Thrust} &= L \cos e - D \sin e. \\ \text{Torque} &= (L \sin e + D \cos e) r.\end{aligned}$$

has been shown by the curves in Fig. 51. The increase, when climbing, may be obtained by a decrease in V or an increase in N , or both.

Negative blade angle of attack for zero thrust. — As the angle of attack decreases (with decrease of slip and increase of V/N) the lift, and so the thrust, decreases; but at zero angle of attack there is still some lift and thrust. As with any airfoil there is a certain negative angle of attack at which there is no lift (as shown in Fig. 11, page 20), so with a propeller element there is a certain negative angle of attack at which there is no thrust. The resultant path of a blade element is then as indicated by the dotted line OF in Fig. 60, in advance of the chord of the blade element, instead of back of it as shown by OP for positive angle of attack.

The angle between OF (the resultant path for zero thrust) and the direction of rotation OB , is the **zero-thrust pitch angle**, and the corresponding pitch is the **zero-thrust pitch**.

To obtain positive thrust, the effective pitch angle e must be less than the zero-thrust pitch angle, by an amount dependent upon the slip.²⁰

Angle of blade attack and thrust at standstill. — The angle of blade attack increases as the airplane velocity decreases and has its maximum value at standstill when $V = 0$. The angle of blade attack α is then equal to the blade angle a .

Since $\tan a = p/\pi$, where p is the geometrical pitch ratio as shown in a preceding note, the blade angle or value of blade angle of attack at standstill, corresponding to any value of p , can be readily calculated. The following values are thus obtained.

Pitch ratio, p	0.5	1.0	1.5	2.0
Blade angle, a	9°	$17\frac{1}{2}^\circ$	$25\frac{1}{2}^\circ$	$32\frac{1}{2}^\circ$

The thrust of a propeller at standstill depends upon its lift as an airfoil, and this is a maximum when the angle of attack is between 12° and 18° , varying with the shape of the blade or airfoil (see

²⁰ Slip varies as the difference between the tangents of the two angles if the older definition of slip is accepted.

pages 19 and 23). It is seen, therefore, that to obtain the maximum thrust at standstill, — i.e., the maximum static thrust — a propeller should have a certain pitch ratio, between let us say 0.7 and 1.0, a larger or smaller pitch ratio giving less airfoil lift and so less static thrust.

While it is not necessary to have a pitch ratio that will give the maximum static thrust, it is necessary to have a pitch ratio that will give sufficient thrust to get under way and accelerate on a bad field. This is a reason for not employing very high or very low pitch ratios.

L/D ratio for propeller: — The L/D ratio for a propeller section has a maximum value of about 20, when the blade angle of attack is, say, 4° or 5° . It is sought in propeller design and operation to approach a maximum value in this ratio (or rather in the thrust to torque ratio) but there are limitations in structure that make this difficult.

Blade shape. — The problem of determining the several sections for a propeller blade is much the same as that of determining the section for any airfoil, although there are differences due to the helical path in one case and the straight path in the other, and consequent differences in the eddies and vortices produced.

The front surface of a propeller blade (the upper surface, considered as an airfoil in the usual manner) is highly cambered. The amount of this camber and its distribution depend somewhat upon the intended service. The back surface is flat, or nearly so, for it is found that there is little or no gain in shaping this surface. Aspect ratio enters in blade design much as in the design of any airfoil. To obtain the advantage of high aspect ratio, a long and narrow blade is used for an air propeller. (Not so for a marine propeller.)

The greatest thrust and torque in a propeller blade are obtained toward the tip, the maximum being about $\frac{4}{5}$ the way from hub to tip.

Wooden propellers are made with aspect ratios from 4.5 to 6.5. Because of their higher strength metal propellers may have aspect

ratios as high as 8. The plan-forms of several types of propellers are shown in Fig. 62a.

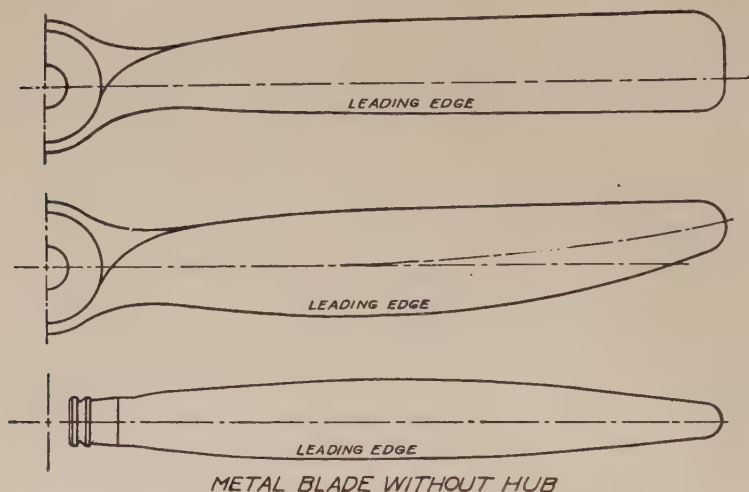


FIG. 62a. Planforms of several types of propellers.

Mechanical strength is an important consideration in propeller design. Changes in blade shape that produce little change in aerodynamic efficiency may have a large effect upon strength. In fact in propeller design the question of strength is foremost. Particularly true is this as the hub is approached, for this part of the propeller — on account of its lesser velocity of rotation — contributes little to thrust, so that strength is here practically the entire problem. High polish is given the blade to reduce resistance. The surface is given a waterproof finish to avoid absorption of moisture and consequent warping.

Very important is a proper **propeller balance**, a slight unbalancing at high velocities of rotation causing forces that soon become destructive.

Uniform and variable pitch; mean pitch. — When a propeller is constructed with the same geometrical pitch at all parts, from hub to tip, the pitch is said to be **uniform**. When the pitch varies from

hub to tip, the pitch is said to be **variable**. A mean value for pitch is then sometimes given, but the determination of mean pitch is somewhat arbitrary. It has been found that a variable pitch gives no gain in aerodynamic efficiency.

Adjustable-pitch propellers. — A propeller with a fixed blade angle and therefore fixed pitch gives a maximum value of L/D and maximum efficiency at only one value of V/ND . A propeller which allows change of pitch in flight with change of operating conditions extends the high value of L/D over a greater range of pitch ratio, giving a flatter top to the efficiency curve. Propellers of this type do not give as good performance as do fixed-pitch propellers designed for the same operating conditions, because changing the pitch by changing the blade angle changes each element of the propeller blade the same angular amount. To get best efficiency, each element of the propeller would have to be changed a different angular amount.

The operating mechanism for changing the pitch of a propeller in flight must be contained in the hub of the propeller. The design of a mechanism that will operate satisfactorily with minimum effort on the part of the pilot is very difficult and has not been satisfactorily worked out as yet. Metal propellers, with blades that are detachable and adjustable for various blade angles when the propeller is stationary, are in common use. Tests on such a propeller at different blade angles give the same results as would a series of tests on several propellers of like proportions but different pitches.²¹ An adjustable-pitch propeller in which the pitch can be reversed is useful in stopping the airplane after landing, the thrust obtained being negative with the pitch reversed. However the added weight and complication of such a device offsets the advantages to be obtained from its use.

Effect of airplane structure on propeller performance. — If a propeller is tested in a wind tunnel on the end of a slender shaft of

²¹ See National Advisory Committee for Aeronautics Technical Report No. 306, 1929, for results of wind tunnel tests on a metal propeller as described above.

$$\text{efficiency of prop} = \frac{v + av}{v + a} = \frac{1 + a}{1 + a}$$

such length and diameter that the obstruction to the slip-stream is negligible, it is found that less thrust is produced than when tested with an airplane fuselage close behind it, as in an ordinary mounting. If the drag on the fuselage is measured with the propeller in operation and again with the propeller removed but with the same air velocities, it is found that the drag of the fuselage is larger when the propeller is operating than when it is removed. Since there is an increase in thrust and an increase in drag caused by the interaction between the propeller and the airplane structure, the net result will depend on which is the larger percentage increase.

The increase in thrust is explained by the air being slowed down as it nears the obstructing airplane structure, thus giving an increased thrust (maximum thrust being static thrust). The increase in drag is caused by the increase in the velocity of the air flowing by the parts of the fuselage in the slip-stream, the drag going up as the square of the velocity.

Tests ²² show that the propeller efficiency is decreased slightly by the interaction between the propeller and the airplane structure. The zero-thrust pitch ratio is also slightly increased by the above effect. These effects can be partially eliminated by increasing the clearance between the propeller and the fuselage.

Value of the airfoil theory. — Of most importance is the scientific basis upon which the airfoil theory has established propeller theory. Previous to the proposal of the airfoil theory for propeller action, little was understood of how it acted or why it produced thrust. This resulted in experimentation being carried on blindly, with no system or scientific backing. Fundamental data on propeller actions must yet come from experiments, but with the airfoil theory as an explanation of propeller action, these experiments may be planned and carried out scientifically and systematically.

An understanding of the propeller as an airfoil also enables

²² National Advisory Committee for Aeronautics Reports Nos. 177 and 235.

$$2a+1 = \sqrt{1 + \frac{8Kc}{\pi V^2}} \quad (.85)$$

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one to explain or predict the performance of the propeller, knowing the conditions under which it will operate, since it makes clear the relations between the quantities affecting its operation. It has been the purpose of this chapter to give the reader the fundamentals necessary for such an understanding of the propeller and its operation.

J = pitch dia. ratio

$$J = \frac{V}{ND}$$

$$T = 2A(V+v)Pv$$

This is the relation between thrust and velocity; valid for propulsive and disc area or for windmill

Torq CV = power ^{input} output into prop and if screw is working as a windmill this equals —

$$\begin{aligned} & \text{Work done per sec on air} \\ & = \text{gain in K.E. of fluid per sec} \\ & = T(V+v) \end{aligned}$$

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CHAPTER VII

RELATION BETWEEN POWER REQUIRED AND POWER AVAILABLE

In Chapter V it was found that the power required for horizontal flight depends upon the lift and drag coefficients, as determined by the shape of the wing-section, upon the parasite drag, and upon the wing loading, the ratio of the airplane weight to the wing area. In Chapter VI it was found that the power available for propelling the airplane depends upon the characteristics of the combined unit of engine and propeller. For sustained flight the power available must be equal to or greater than the power required for horizontal flight, as determined by the loading and the aerodynamic characteristics of the wing-sections.

The variation of power required and power available with different conditions of flight is shown in Chapters V and VI, respectively.

The variation of power required with velocity is shown by the U-shaped curves, Figs. 39-43. The variation of power available with velocity is shown by the Ω -shaped curves in Figs. 53 and 58, in the preceding chapter.

Value of an understanding of the relation between the power required and the power available. — There are three things of importance that will be gained from an understanding of the relation between the power required and the power available.

First, with a given airplane and engine and propeller characteristics, the best condition for operation with respect to climbing, maximum velocity, minimum velocity, etc., may be determined.

Second, the essential features in airplane operation, with respect to throttle and elevator control and their relation to airplane operation and angle of attack of the wings with the relative air, will be explained.

Third, having given an airplane which is required to perform in a specified manner with reference to climbing or speed, either maximum or minimum, an engine and propeller unit which will enable the airplane to fulfill the requirements, may be chosen.

The following paragraphs will explain more fully the above statements.

Power available must be equal to or greater than the power required. — In Figs. 63-66, the U-shaped curve P_1 represents power required and the Ω -shaped curve P_2 represents the power

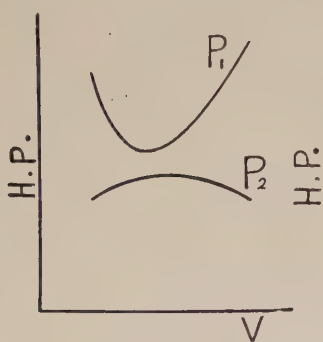


FIG. 63

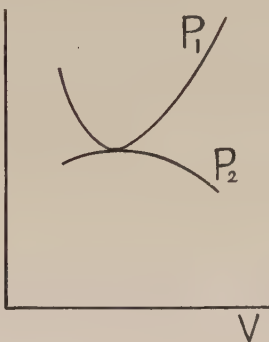


FIG. 64

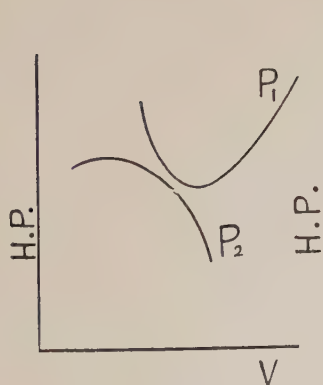


FIG. 65

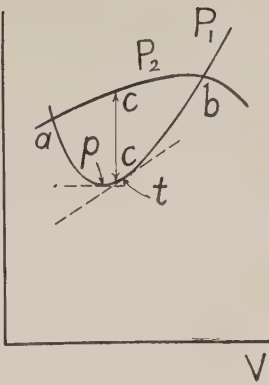


FIG. 66

Relation between power required P_1 and power available P_2 .

available, at different velocities. When the power available is, at every velocity, less than the power required, as in Fig. 63, it is obvious that maintained flight is not possible. Furthermore, it is scarcely possible when the power available is just equal to the power required at one particular velocity, as in Fig. 64, for with this condition ¹ it would be necessary to maintain this precise velocity without variation; any slight increase or decrease in velocity would cause the airplane to lose altitude.

Again, even though the engine and propeller are capable of delivering a maximum power available greater than the minimum value of the power required, maintained flight is not possible when, as in Fig. 65, the power is available at one range of velocities and is required at a different range of velocities. With these conditions the airplane is designed for one velocity, the propeller and engine for another; and, at the velocity at which the airplane must fly, the power available is insufficient. The condition shown in Fig. 65 might occur if a propeller with too low a pitch were used.

Practically, therefore, for maintained flight, the power available must be more than the power required over a certain range of velocities, as shown in Fig. 66. The limits of this range are shown by the points *a* and *b* at which the power available and the power required are equal. The minimum flying velocity at *a* and the maximum flying velocity at *b* are thus determined. See also Figs. 67 and 68.

Beyond this range maintained flight is impossible, for at a higher or at a lower velocity the power available is less than the power required. Thus, a particular machine might be able to fly

¹ This condition, with the curves P_1 and P_2 tangent as shown in Fig. 64, occurs when a machine attains its maximum altitude, called the *ceiling*, discussed later under Altitude. Near the ground the relations between P_1 and P_2 are as shown in Fig. 66, but the curves P_1 and P_2 shift, as altitude is increased, so as to give less surplus power and at the ceiling the two curves touch each other at one point only, showing that there is no surplus power. The point of tangency of the curves P_1 and P_2 is not necessarily at the minimum point of P_1 and the maximum point of P_2 (as in Fig. 64); but may be as in Fig. 65, if the curves P_1 and P_2 were slightly shifted so as to be tangent.

in horizontal flight at any velocity between, say, 45 and 100 MPH., but at no higher or lower velocity.

Surplus power. Referring to Fig. 66, it is seen that within the range of flying velocities, there is an excess of power available over power required. This excess is called **surplus power**. It is surplus power that causes a machine to climb, the rate of climb being directly proportional to the amount of surplus power, as discussed in the next chapter.

The surplus power cc , Fig. 66, is a maximum at one particular velocity, and this, accordingly, is the velocity for best rate of climb. Maintenance of this velocity depends upon the judgment of the pilot in keeping the airplane in correct flying position. For higher or lower velocities the surplus power is less, and becomes zero when the velocity has its minimum value for sustained flight at a or its maximum value at b .

In Fig. 66, the point p is the point of minimum power and t the point of minimum thrust required for horizontal flight as previously discussed. (The dotted line tangent to the power curve at t , if prolonged, would intersect the horizontal axis at the origin, not shown in this figure, where $V = 0$; see Fig. 43a.

The minimum thrust t is always at a higher velocity than the minimum power p . No general statement can be made as to the velocity for maximum surplus power; it may be at a higher velocity than t or at a lower velocity than p , depending upon the relation between P_1 and P_2 , or at a velocity between p and t as in Fig. 66. See also Fig. 69.

Power relations for different R.P.M. and for different throttle openings. — The relation between power required and power available is more completely shown in Figs. 67 and 68. In each of these figures a curve is given for the power required for horizontal flight at different velocities by a particular assumed airplane. The point of minimum velocity, indicated by a_0 in each figure, is the *absolute* minimum velocity and this depends upon the aerodynamic characteristics of the airplane, irrespective of engine and propeller.

The curves for power available are drawn for different R.P.M.

in Fig. 67 and for different throttle openings in Fig. 68, these curves being determined in the manner described in the preceding chapter.¹

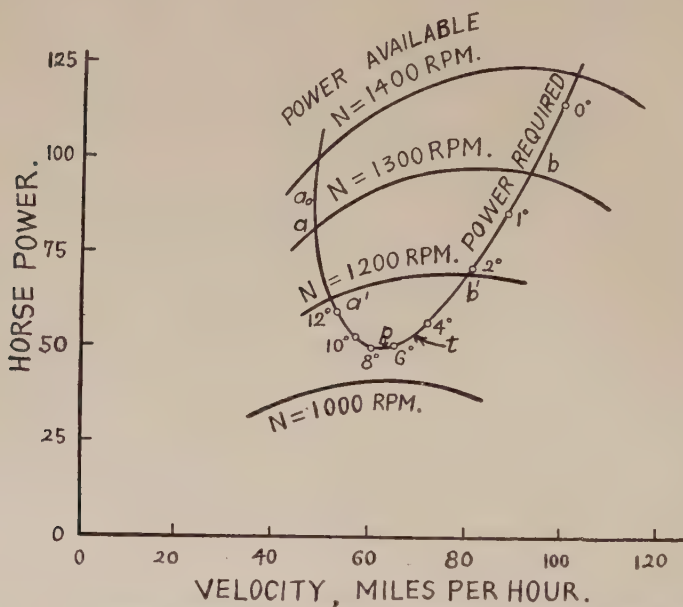


FIG. 67. Power required for flying a particular airplane at different velocities; points marked show corresponding angles of attack. Also power available from a particular propeller (any engine) driven at various R.P.M. a and a' are minimum, b and b' maximum, velocities at different R.P.M. a_0 is absolute minimum velocity. p is minimum power, t is minimum thrust, for horizontal flight.

In Fig. 67, the limits of velocity are at a and b when the propeller has a speed of 1300 R.P.M., and at a' and b' when the propeller has a speed of 1200 R.P.M. At these limits the power available is just equal to the power required for horizontal flight. Between these limits there is a surplus power for climbing. Beyond these limits the power available is less than that required for horizontal flight and the airplane must consequently descend.²

¹ See Figs. 53 and 58.

² When the velocity is less than that corresponding to a_0 , the descent may be in an oblique path, or it may be a stall leading to a fall.

Similarly, in Fig. 68, the limits of velocity with full throttle are shown at a and b ; for $\frac{7}{8}$ throttle, at a' and b' ; for $\frac{3}{4}$ throttle at a'' and b'' . It is seen that any decrease in power available limits the range between minimum and maximum velocity by increasing the minimum and decreasing the maximum.

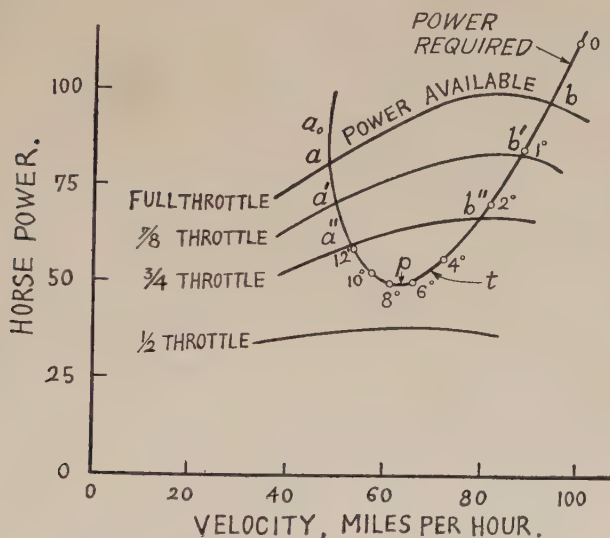


FIG. 68. Power required for a particular airplane, also power available from a particular propeller and engine, with different amounts of throttle. Minimum velocity is at a (absolute minimum at a_0); maximum velocity is at b . p is minimum power, t is minimum thrust, for horizontal flight.

As a matter of fact, the power available when flying near the ground is ordinarily sufficient so that the minimum velocity is the absolute or aerodynamic minimum and is determined by a_0 . From page 38, this minimum velocity is seen to be

$$V_{\min.} = \sqrt{\text{loading}/\text{maximum } K_L}.$$

The maximum value of K_L varies but little in machines of a given type; indeed, even in machines of different types the range of variation in the maximum K_L is small, — say, twenty per cent. Loading, on the other hand, may vary several hundred per cent.

Minimum velocity, therefore, is chiefly determined by the loading, see Fig. 20. A small loading indicates a low minimum velocity. Frequently the minimum loading is specified and no other specification of minimum velocity is given.

On the other hand, the maximum velocity is determined by the amount of power available in relation to the power required.

Generally speaking, curves for power available from a propeller are more useful when drawn, as in Fig. 67, so as to be independent of the engine employed, — assuming only that an engine is used that can give necessary power. From the standpoint of the pilot, however, the curves in Fig. 68, relating to a particular engine as well as a particular propeller, are instructive, for he is most interested in his particular engine and its control.

Control of power relations in flight. — Two controls operated by the pilot affect the power relations in flight, namely, **elevator control** and **throttle control**.

The elevator control determines the angle of attack, and hence the corresponding values of velocity and power required, as shown by the curves for power required in Figs. 67 and 68. Any adjustment of the horizontal stabilizer ³ in flight has the same effect as an adjustment of the elevator, and may, accordingly, be considered as elevator control.

The throttle control determines the number of revolutions per minute of the engine and propeller and the amount of power available. If, for example, the pilot keeps the number of revolutions per minute constant at 1400, 1300, or 1200, the power available from a particular propeller at different airplane velocities is as shown by the several curves in Fig. 67. Or, if the pilot keeps full throttle, $\frac{7}{8}$ throttle or $\frac{3}{4}$ throttle, the power available from a partic-

³ The setting of the horizontal stabilizer in some machines can be made only on the ground, in other machines it may be made in flight; but in any case the change in setting is only occasional, whereas the control of the elevator is continuous. The horizontal stabilizer may be set so that a machine will climb or so that it will fly horizontally, with the elevator control in a neutral position, thus requiring less effort on the part of the pilot either when climbing or when flying horizontally, as the case may be.

ular propeller when driven by a particular engine is shown by the curves in Fig. 68. Under throttle control may be included any engine adjustment that affects the amount of power developed, as carburetor adjustment and the timing of ignition, the curve for full throttle showing the greatest power available when all adjustments are made.

Control by the elevator, for any given position of the throttle, is affected by the pilot almost unconsciously. Thus, when flying horizontally with 2° angle of attack and 1200 R.P.M. (Fig. 67), if the pilot increases the R.P.M. to 1300 by opening the throttle, he maintains the flight path horizontal by decreasing the angle of attack to 0.5° by a slight and almost imperceptible change in the position of the elevator.

It is thus seen that for horizontal flight any change in power available (brought about by change of R.P.M., controlled by the throttle) must be accompanied by a like change in power required (brought about by a change in angle of attack, controlled by the elevator).

If power available and power required are not thus maintained equal, the flight path is no longer horizontal, as discussed more fully in the next chapter. Whenever the power available exceeds the power required, there is surplus power and the machine climbs. Whenever the power available is less than the power required, the machine takes an oblique path downward. In order to climb, a pilot puts on power and by elevator control noses up, thus increasing his angle of attack and decreasing his velocity, until he has the requisite surplus power cc , Fig. 66.

Normal and reverse control. — In the case illustrated in Figs. 67 and 68, minimum thrust t would be required at a velocity about 70 MPH. and at an angle of attack of about 5° ; minimum power p would be required at a lower velocity, about 64 MPH., and larger angle of attack, about 7° .

Flying is usually at higher velocity and smaller angle of attack, than correspond to either p or t , being nearer the point b of maximum velocity. In the normal flying range between p and b , an

increase in velocity involves an increase in the power required; a decrease in velocity involves a decrease in power required.

But at lower velocities than the velocity for minimum power, namely, between g and a in Figs. 67 and 68, this relation is reversed: a decrease in velocity requires more power. This is designated as the range of reverse throttle control.

Flight in the range of reverse control demands more skill on the part of the pilot, not only on account of the reversal of control, but even more on account of the decrease in stability at low velocities, for all airplane stability depends upon velocity. Low velocities, however, are desirable in making a landing. Otherwise, they may well be avoided by the novice.

Comparison of machines. — The curve of power required depends upon the aerodynamic characteristics of the machine. It depends on the engine and propeller only in so far as these parts change the aerodynamic characteristics of the machine. The curve of power available depends solely upon the engine and propeller

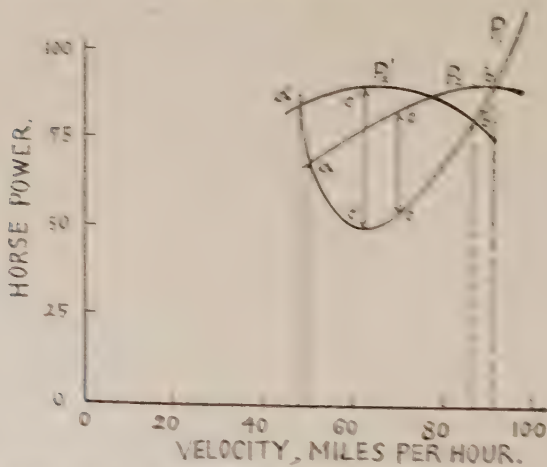


FIG. 66. Comparison of power plants. P is power required by a particular airplane. P' and P'' show power available from two power plants, each with the same maximum power. P' gives higher minimum and maximum velocities, a' and b' , while P'' gives more surplus power, c'' .

disadvantaged. The above and position of these two curves are partly open to question. The relation between the two curves must cover the performance of the complete machine.

For example, let P_1 be Fig. 16, the power required for a vertical climb. There are available two power plants and of course power is not available P_1 , and the other gives power available P_2 , the maximum power available from each machine being the same. Which is the more convenient?

The choice evidently depends upon the manner in which the engine is to be used. With the first power plant, giving power available P_1 , the maximum and minimum velocities are u and v , respectively, and the maximum available power is u^3 . With the second power plant, giving power available P_2 , the maximum and minimum velocities are u' and v' , respectively, and the maximum available power is u'^3 . It is evident that the first power plant, giving power P_1 , will give the highest level of the maximum of climb or descent. It also necessitates a high landing speed. The second power plant, giving power P_2 , gives the lowest landing climb and lower landing speed, although the maximum speed available is not so great.

The two power plants might consist of the same engine employed with different propellers. The higher pitched propeller would give power P_1 and the lower pitched propeller would give power P_2 . Their great climbing ability at take-off is based in comparison with high speed climb flight is desired, a propeller whose pitch can be varied so flight could be used to advantage the low pitch being good for take-off and climbing and the high pitch for speed. This is especially true of airplanes and for biplanes and flying boats a very heavy kind of fuel must be gotten into the air at the start. Consider a propeller with a fixed pitch or fixed, the propeller being a compromise between the one that would give the best climb and the one that would give the highest speed.

Effect of altitude on power required and power available. — As the altitude of the airplane is increased the density of the air decreases. As a result, at a given altitude, a propeller, say, will have

its power output decreased. If a supercharger is used the engine will continue to deliver the same power as at sea level until such an altitude is reached that the supercharger can no longer supply air to the engine at sea level density.

Assuming that the engine is equipped with a supercharger so that the engine output does not change with ordinary altitudes, there will still be a change in the power available curve with altitude. The effect of increased altitude on the propeller performance is the same as if the pitch of the propeller were gradually reduced as the altitude is increased. To get the same propeller output the pitch would have to be increased as the plane gained altitude. It is evident then that the power available curve will be affected by altitude, since the decrease in air density affects both the engine and the propeller performance.

The power required curve will also be affected by an increase in altitude since the lift and drag of the airplane are both less in air of low density.

The effect of altitude upon the power required and power available will be considered more in detail in the chapter on Altitude.

$$k_P = P_c J^3 = \frac{P}{\rho N^3 D^5}$$

$$P_c = \frac{P}{\rho V^3 D^2}$$

$$\eta = \frac{1}{1+a}$$

CHAPTER VIII

CLIMBING AND GLIDING

When the power delivered by an airplane propeller is not equal to the power required for the plane to fly horizontally at that velocity, the machine travels an oblique path upward or downward, depending on whether the power supplied by the propeller is greater or less than that required for horizontal flight. This chapter will explain the performance of the airplane when operating under such conditions that the power required and power available are not equal.

OBLIQUE PATH UPWARD

Climbing angle and rate of climb. — When an airplane takes an oblique path upward it is said to **climb**. The **climbing angle** is the angle which the inclined flight path makes with the horizontal, shown in Fig. 70 as the angle c .



Fig. 70. Climbing.



Fig. 71. Gliding.

The **climbing velocity** or **rate of climb** is the vertical component V_c of the velocity V of the airplane along its flight path as shown in the figure. The relative values of V and V_c determine the climbing angle c ; thus

$$\sin c = V_c \div V; \quad V_c = V \sin c.$$

The climbing velocity is equal to the velocity along the flight path multiplied by the sine of the climbing angle.

Velocity in oblique flight. — Velocity along the flight path in oblique, as well as in horizontal, flight is determined by the formula for lift,

$$L = K_L S V^2,$$

where L is the total lift from *all* sustaining surfaces. In horizontal flight $L = W$ and

$$V = \sqrt{\frac{W}{SK_L}}.$$

This expression for velocity is likewise approximately true in oblique flight when the angle of inclination of the flight path is small.

This approximation, while sufficiently accurate for most purposes in connection with climbing, is not justified in gliding and diving, when the angle of inclination may be large. This is discussed later.

More accurately ¹, $L = W \cos c$, where c is the angle of inclination of the flight path. In case of gliding, this is shown in Fig. 75. It will be seen that, when the angle of inclination is small, it is very nearly true that $L = W$. Thus, when $c = 5^\circ$, $L = 0.996W$; when $c = 10^\circ$, $L = 0.985W$; when $c = 15^\circ$, $L = 0.966W$, etc. Indeed, for small angles this error is probably less than various incidental errors in the calculation.

Surplus power is used for climbing. — In horizontal flight, the power required for airplane flight is the power necessary to overcome airplane resistance; expressed in horse power this is $VR/375$, where V is velocity of the airplane relative to the air in miles per hour and R is total airplane resistance in pounds.

The additional power P_c used in climbing is $V_c W/375$, where V_c is the vertical velocity in miles per hour and W is the total weight of the machine in pounds.

¹ This holds when thrust is in line with resistance; in this case W is the hypotenuse of a right triangle of which the other two sides are L and $T - R$. In any case weight is the sum of the vertical components of L , R and T , with proper sign; thus, $W = L_v + T_v + R_v$.

The total power necessary when climbing is, therefore,

$$\text{Power} = VR/375 + V_c W/375.$$

The power used in climbing is the so-called surplus power, i.e., the excess of power available over the power required for horizontal flight.

Rate of climb is proportional to surplus power divided by weight.

— When the weight of a machine is known, its rate of climb may be readily calculated from its surplus power. As shown above the surplus power is

$$P_c = WV_c/375.$$

The climbing velocity is, accordingly,

$$V_c = 375 P_c \div W, \text{ miles per hour,}$$

or, $V_c = 33,000 P_c \div W, \text{ feet per minute.}$

The rate of climb is thus seen to be proportional to the *surplus power per pound*. A heavier and more powerful motor, by increasing surplus power more rapidly than the total weight, accordingly increases the rate of climb. The surplus power, and the consequent rate of climb, varies with airplane velocity.

Maximum rate of climb. — The rate of climb is evidently a maximum when the surplus power is a maximum; it is obtained, with the throttle wide open, at a definite airplane velocity and corresponding angle of attack. The airplane velocity for best climb is often known to the pilot; it may to a certain extent be sensed in flight or determined from the altimeter by noting the rate at which altitude is being gained.

As surplus power is less at high than at low altitudes, the rate of climb becomes less as a machine ascends and finally becomes zero for a given machine at a definite altitude called the "ceiling," beyond which it cannot climb, as discussed in the next chapter.

Illustrative example. — In Fig. 72, P_1 represents the power required by a particular airplane, that is, the power required to

overcome airplane resistance, or the power required for horizontal flight. P_2 represents the power available. The excess of P_2 over

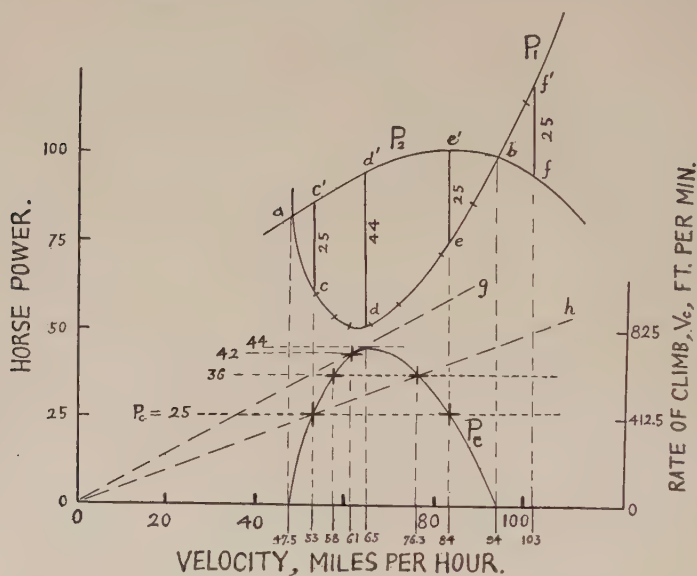


FIG. 72. Surplus power P_c is the excess of power available P_2 over power required P_1 . Rate of climb is proportional to surplus power.

P_1 , — as cc' , dd' , etc., — is the surplus power P_c used in climbing; these values for surplus power are plotted below as the curve P_c . At the intersections a and b , P_1 and P_2 are equal and there is no surplus power; these points determine the minimum and maximum velocities for horizontal flight, in this case 47.5 MPH. and 94 MPH., respectively.

As the rate of climb is proportional to the surplus power, the curve P_c for surplus power may also be taken as a curve for rate of climb, by using a proper scale depending upon the total weight of the airplane. At the right hand of Fig. 72 is shown the scale for rate of climb in feet per minute when $W = 2000$ lbs.

It is seen that the same surplus power, and so the same rate of climb, may be obtained at two different velocities. Thus, the sur-

plus power is 25 H.P. at 53 MPH. and also at 84 MPH., the rate of climb in each case being

$$V_c = 33000 \times 25 \div 2000 = 412.5 \text{ ft. per min.} = 4.69 \text{ MPH.}$$

Although the rate of climb is the same, the climbing angle is different in the two cases, for $\sin c = V_c/V$; the higher velocity gives the smaller climbing angle.

Thus, in this case, the climbing angle is 5° at 53 MPH., and 3° at 84 MPH. ($4.69/53 = 0.088 = \sin 5^\circ 3'$; $4.69/84 = 0.0558 = \sin 3^\circ 12'$.)

In Fig. 72, a horizontal line (as $P_c = 25$, or $P_c = 36$) intersects the curve for P_c at two points that have the same rate of climb. A diagonal line, as oh drawn from the origin, intersects the curves for P_c at two points that have the same climbing angle, for P_c/V has the same value in each case. Thus, as shown above, at 53 MPH., when $P_c = 25$, the climbing angle is 5° ; the rate of climb being 412.5 feet per min. At 76.3 MPH., when $P_c = 36$, the climbing angle is also 5° ; the rate of climb being 594 feet per min. The maximum climbing angle is determined by the point where the line og drawn from the origin is tangent to P_c , for P_c/V is then a maximum. It is evident that the speed thus determined is the best climbing speed for clearing obstacles.

It is thus seen that for every low velocity, it is possible to select a higher velocity that will give the same climbing angle with greater rate of climb, or a still higher velocity that will give a smaller climbing angle with the same rate of climb.

For a given rate of climb, the *high velocity with small climbing angle* is much safer than the low velocity with large climbing angle. The low velocity gives greater chance for stalling and should generally be avoided, but may be necessary in certain maneuvers and in avoiding trees or like obstructions.

There is a wide difference in the climbing ability of different machines. One may have little surplus power and leave the ground slowly; Fig. 72 may be taken as an illustration of such a machine. Another, with ample surplus power, may shoot up with a vertical

velocity of 25 or 30 MPH. Some high powered racing planes are capable of climbing at the rate of a mile a minute.

The climbing angle and rate of climb throughout this discussion relate to steady climbing and not to short spurts. After acquiring sufficient momentum, a machine may for a moment climb at a much greater angle than its steady climbing angle. This is called **zooming**. It is often possible to zoom over an obstruction, the velocity lost thereby being subsequently regained by levelling out or even descending a little.

Procedure in starting and climbing. — In leaving the ground a machine must climb. The ordinary procedure in starting is as follows:

The engine is started and as soon as the airplane is released the pilot by use of the rudder keeps a straight course with full power ² into the wind, keeping on the ground until a velocity well above the minimum flying velocity is reached. After the first few feet the pilot pushes the control forward, thus depressing the elevator, which raises the tail of the machine from the ground; he then gradually moves the control back and holds the machine rolling on the ground in normal horizontal flying attitude, until flying velocity is reached. The control is pushed forward if necessary at any time to prevent the machine from leaving the ground too soon. The wings are kept level by lateral control.

When well above the minimum flying velocity, the control is pulled back a little so that the machine noses up and leaves the ground, ascending steadily at a *small climbing angle* and *high velocity*, until a considerable altitude is reached.

Too large a climbing angle will result in a stall, with loss of velocity and loss of sustentation. Although it is possible for an experienced pilot, by a slight backward movement of the control, to leave the ground at minimum flying velocity, this should be avoided as it gives no margin of safety in case of trouble. It is well to know in advance the airplane velocity for best climb. *Safety*

² Some engines will not stand full throttle until a certain altitude is reached.

lies in a straight course into the wind, high velocity and small climbing angle. Ability to start in a cross wind is acquired with experience. Turns³ near the ground, particularly at low velocities, are

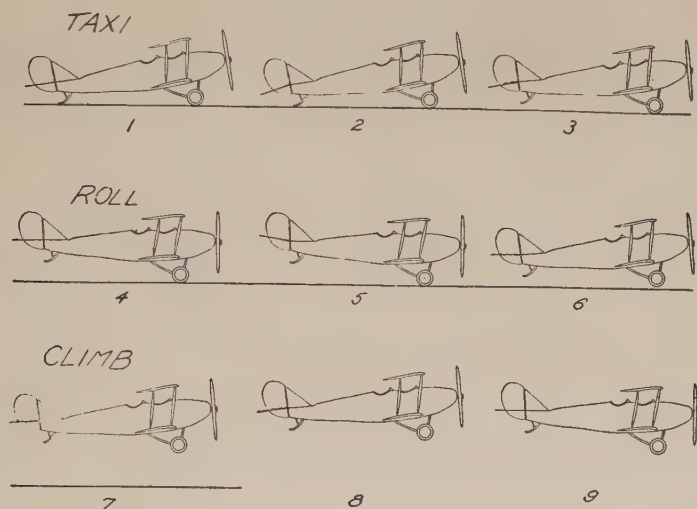


FIG. 73. Operation in starting and climbing. The pilot at first starts to "taxi" (1). Then, opening the throttle and passing immediately through (2) and (3) by depressing the elevator and thus raising the tail of the machine, he increases velocity while "rolling" (4). He "takes off" or leaves the ground (5, 6) by raising the elevator when sufficient velocity is attained, climbs (7) and straightens out (8, 9) when the desired altitude is reached.

to be avoided. Some rules for safe operation, given at the end of this chapter, may be here noted.

As pointed out elsewhere, some machines are balanced so as to climb when the control is in neutral, thus requiring little attention after leaving the ground until considerable altitude is reached.

The usual procedure in starting and climbing is illustrated in Fig. 73.

³ In making a turn with a low powered machine it is advisable to nose down, especially if near the ground or if the pilot is inexperienced, in order to maintain velocity and avoid the possibility of a stall or loss of control. There is a tendency for a machine to lose velocity on a turn due to increase of resistance, as explained in a later chapter on Directional Stability.

OBLIQUE PATH DOWNWARD WITH POWER ON

When there is a deficit of power instead of a surplus, a machine takes an oblique path downward. — When the power available is less than the power required for horizontal flight, there is a deficit of power instead of a surplus, and P_c is negative. The vertical velocity V_c in this case is negative, that is, it is a **rate of descent** and not of climb. The machine takes an oblique path downward, the flight path making an angle c with the horizontal, as shown in Fig. 71. As before, $\sin c = V_c/V$.

For example, as shown in Fig. 72, suppose 118 horse power is required for horizontal flight at 103 MPH., while at this velocity only 93 horse power is available. The deficit, shown as ff' , is $P_c = -25$. The rate of descent, when $W = 2000$ lbs., is $V_c = -33000 \times 25 \div 2000 = 412.5$ ft. per min. or 4.69 MPH. The angle of descent c is between 2° and 3° ($4.69/103 = \sin 2^\circ 37'$). It is seen that negative values of V_c and c are calculated in the same way as positive.

In the foregoing example, of the 118 horse power required to overcome air resistance, 93 horse power is supplied by the power plant and 25 horse power is supplied by gravity. *Gravity is used as a source of power.*

GLIDING AND DIVING

Gliding is a special case of oblique flight downward in which all the power is supplied by gravity, the power from the power plant being cut off and the angle of inclination of the flight path being small. Gliding becomes diving when the inclination of the flight path is large. There is no sharp line between gliding and diving; the same laws apply to both.

Gliding angle is determined by the ratio of resistance to weight. — In gliding, the power supplied by gravity $V_c W/375$ is equal

to the power $VR/375$ used in overcoming air resistance, for there is no other source of power or expenditure of power. Hence,

$$\begin{aligned} VR &= V_c W; \\ V_c/V &= R/W = \sin c. \end{aligned}$$

The gliding angle is thus determined by the ratio of resistance to weight; for an airplane of given weight the gliding angle is determined solely by its resistance. The value of the resistance depends upon the angle of attack and corresponding velocity.

For example, a machine which weighs 2000 lbs. has a resistance of $333\frac{1}{3}$ lbs., when flying at a certain velocity and angle of attack. The gliding angle is $c = 9^\circ 36'$. ($R/W = 0.166 = \sin 9^\circ 36'$.) It will be shown later that changing the weight of a certain machine by changing its load will cause no change in the gliding angle c , for the change in weight will cause a proportional change in resistance so that R/W remains constant.

Length of glide or gliding range. — The gliding range depends upon the gliding angle. Let d be the length of glide, measured along the flight path; and let h be the vertical distance through which the airplane descends. The length of glide is

$$d = h/\sin c = h \times W/R.$$

Thus, in the preceding example, $\sin c = 1/6$; hence, $d = 6 h$. That is, if the resistance of an airplane is $1/6$ of its weight, the airplane will glide six times its initial altitude from the ground. Starting to glide at an altitude ⁴ of one mile, such a machine would glide 6 miles, measured along the oblique flight path. The horizontal distance along the ground, equal to $h/\tan c$, would be somewhat less.

As a practical illustration, if the machine just referred to were a seaplane flying at an altitude of one mile, it should never fly

⁴ When flying at the same angle of attack, V_c and V are greater at high than at low altitudes; but the ratios V_c/V and R/W are constant and the gliding angle remains unchanged. This is discussed further in the next chapter.

at a greater distance inland than 5 or 6 miles, in order to insure a safe landing in case of trouble. The gliding range with some machines is 10 or more times the initial altitude. A pilot should always keep in mind the possibility of making a forced landing in case of engine trouble.

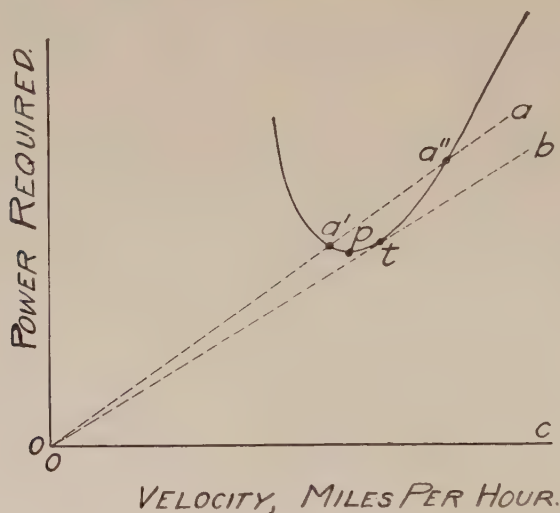


FIG. 74. Minimum drag and best glide is at t where ob is tangent to the curve of power required. Minimum power and minimum rate of descent is at p . Any two points as a' a'' , on a line oa drawn from the origin, have equal drag and the same gliding angle.

Conditions for best glide. — For a machine of given weight, the gliding range is a maximum and the gliding angle a minimum when the resistance R is a minimum.

It has been shown in Chapter IV that the drag of any given machine varies with the velocity at which it is flown and has a minimum value for a particular velocity and corresponding angle of attack, as shown in Fig. 34. This is the velocity and angle of attack giving the minimum gliding angle and maximum gliding range, — and is commonly called the condition for **best glide**. Note also the curves in Figs. 35–38.

The point for minimum drag and for best glide is also shown

in Fig. 74 at the point t , where the line ob is tangent to the curve for power required. Fig. 74 is reproduced from Fig. 43a where it is shown that t is the point for minimum drag (often referred to as minimum thrust) and minimum expenditure of energy.

In Fig. 74, any line as oa cuts the curve for power required at two points a' a'' of equal drag and equal glide, — each of

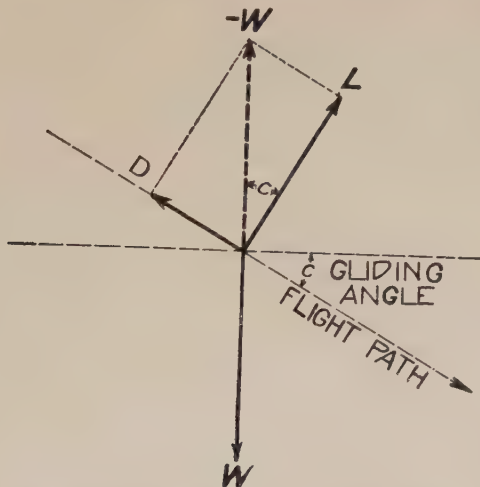


FIG. 75. When power is off, there is no thrust; weight is equal to the resultant of drag and lift. The tangent of the gliding angle c is D/L ; the sine is D/W .

which gives a greater gliding angle and smaller gliding range than the point of best glide t .

The point t , where the energy expended is a minimum, shows the condition for gliding the greatest distance; but the point p , where the power expended is a minimum, shows the condition for gliding the longest time,⁵ i.e., the condition for **minimum rate of descent**, for the rate of descent V_c is proportional to power. (Power = $V_c W / 375 = VD / 375$.)

⁵ A machine weighing W lbs. at height d ft., has Wd ft. lbs. of energy due to its position. It will take the longest time to expend this energy when the rate of its expenditure (power) is a minimum.

Weight balanced by resultant of drag and lift. — In horizontal flight weight is balanced by and is equal to lift; drag is balanced by and is equal to propeller thrust. When thrust is zero, as in gliding, an airplane takes an oblique flight path at such an angle that the resultant of drag and lift is equal and opposite to weight, as shown in Fig. 75.

It is no longer true that $W = L$. It is seen from the figure that

$$L = W \cos c; \quad D = W \sin c; \quad D/L = \tan c.$$

Gliding or diving angle determined by the tangent relation. — The aerodynamic formulas for lift and drag are

$$(1) \quad L = K_L S V^2;$$

$$(2) \quad D = K_D S V^2 + k s V^2.$$

Equation (2) is a statement of the fact that drag consists of two parts, wing-resistance and parasite drag, as discussed in Chapters III and IV.

The gliding or diving angle c is accordingly determined from (1) and (2) by the relation:

$$(3) \quad \tan c = D/L = \frac{K_D S + k s}{K_L S}.$$

The angle c will change as the values of K_L and K_D (and possibly k) are changed by a change in the angle of attack; but the gliding angle, as shown by the tangent relation, is independent of weight.⁶ Increase of weight will increase velocity, as shown below; but, provided the angle of attack is not changed, a change of weight will not change the gliding angle.

Velocity in gliding. — The velocity in gliding is determined from equation (1) above; thus,

$$W \cos c = L = K_L S V^2;$$

$$(4) \quad V = \sqrt{\frac{L}{K_L S}} = \sqrt{\frac{W \cos c}{K_L S}}.$$

⁶ In the expression $\sin c = D/W$, the gliding angle apparently varies with W ; it would seem that increasing W would give a smaller gliding angle. This would be true if D were independent of W . But D varies as V^2 and V^2 varies as W ; so that D varies as W and D/W is not changed by increasing the weight of a particular machine.

For a given angle of attack, K_L , S and c are constant; velocity varies as the square root of weight.

Velocity in diving. — When the angle c is greater than 45° , velocity is best determined from equation (2); thus,

$$W \sin c = D = K_D S V^2 + k s V^2;$$

$$(5) \quad V = \sqrt{\frac{W \sin c}{K_D S + k s}}.$$

Gliding and diving diagram. — Every airplane has a certain gliding angle and velocity, corresponding to each angle of attack, as shown in Fig. 76 for an assumed airplane weighing 2000 lbs. Thus⁷, as shown in the figure, when the angle of attack is -2° the gliding angle is 32° and the velocity 122 MPH. When the angle of attack is -1° , the gliding angle is 18° and the velocity 94 MPH. When the angle of attack is 0° , the gliding angle is 12° and the velocity 80 MPH., and so on. Each point on the curve in Fig. 76 is thus determined by laying off the velocity V at the proper gliding angle, for each angle of attack.

The gliding angle is a minimum at t , where the line a is tangent to the curve. This is the point of minimum drag, which has been designated by t in preceding figures.

The rate of descent is V_e , the vertical component of velocity. The rate of descent is a minimum at p , the uppermost point on the curve. This is the point of minimum power, designated by p in preceding figures.

⁷ Assume $W = 2000$ lbs.; wing-area $S = 333\frac{1}{3}$ sq. ft.; $ks = 0.04$; K_L and K_D , as on page 20. For -2° , $K_L = 0.000346$, $K_L S = 0.115$; $K_D = 0.0000948$, $K_D S = 0.0316$; $K_D S + ks = 0.0716$. The tangent of the gliding angle is $0.0716/0.115 = 0.62$, and the gliding angle is 32° . The velocity is

$$V = \sqrt{\frac{W \cos c}{K_L S}} = \sqrt{\frac{2000 \times 0.85}{0.115}} = 122 \text{ MPH.}$$

The values of gliding angle and V are thus calculated for each angle of attack. For an angle of attack of -3° , when $K_L = 0$ and $K_D = 0.000114$, the velocity is calculated from equation (5); thus,

$$V = \sqrt{\frac{W \sin c}{K_D S + ks}} = \sqrt{\frac{2000}{0.0408 + 0.04}} = 160 \text{ MPH.}$$

It will be observed that when the gliding angle is slightly larger than the minimum, there are two velocities at which the airplane

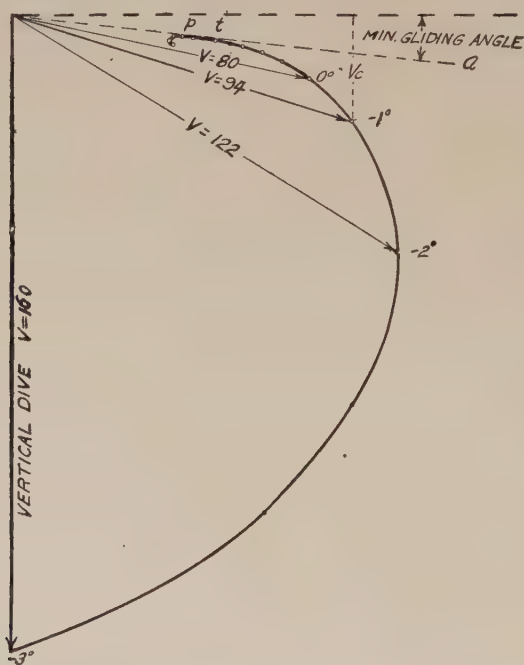


FIG. 76. Gliding and diving diagram, showing the gliding angle and velocity corresponding to each angle of attack for a particular airplane. Change of weight or air density changes the scale for velocity but does not change the gliding angle.

can glide, a low velocity and a high velocity. When gliding at too low a velocity an airplane loses stability and gets out of control; stability and controllability increase with velocity.

It is interesting to note that a small change in the angle of attack from -2° to -3° (the angle at which $K_L = 0$) increases the gliding angle from 32° to a vertical dive of 90° .

Effect of change of weight. — Change of weight merely changes the scale in Fig. 76, for as shown above it changes velocity but does not change gliding angle. An increase in W from 2000 to 3000 lbs. would cause V to be increased by a factor $\sqrt{3/2} = 1.22$; the scale

for V in the drawing, now approximately 50 miles per inch, would become 61 miles per inch. The gliding angle in every case would remain unchanged.

Effect of change of altitude. — Change of density with altitude would likewise change the scale for V but would not change the gliding angle; $V \propto \sqrt{1/\delta}$, as shown in the next chapter.

Effect of Wind Currents on Flight Path. — A simple law of relative motions serves to explain the effect of wind currents on the flight path of an aircraft. To appreciate this law, consider a man (A) walking diagonally across a raft (B) which is moving by the stream banks (C). Reference to Fig. 76a (a) shows that the displacement of (A) relative to the banks (C) is a diagonal of a parallelogram of which the sides are the displacement of (A) relative to (B) and the displacement of (B) relative to (C). Since these displacements all occur in the same interval of time, it is evident that the law applies to velocities as well as to displacements.

To apply this law to the present case, substitute an aircraft for the man, a wind current for the raft, and the ground for the banks of the stream. The law now becomes: *the velocity of the aircraft relative to the ground is the diagonal of a parallelogram of which the sides are the velocity of the aircraft relative to the air (air-speed) and the velocity of the air (wind current) relative to the ground.*

In Fig. 76a, the parallelograms for various conditions are drawn; a study of these diagrams will reveal many interesting things, such as the reason for taking off and landing into the wind, and the reason why a glider, sail-plane, or even an airplane, may gain altitude while gliding, provided it be in a strong up-current of wind.

Gliders and sail-planes. — In the paragraph on "Gliding and Diving" the discussion was limited to the gliding of an airplane in still air. The gliding range as discussed therein referred only to the performance of an airplane in still air. The use of motorless aircraft known as gliders and sail-planes has gained considerable popularity especially in Germany where the original Versailles Treaty put restrictions on aircraft development. Many young

aeronautic students, therefore, concentrated their efforts on the development of motorless flying.

A sharp distinction is made between gliding and sail-flying. During a glide the plane loses altitude steadily until a landing is made. It is necessary, therefore, to start the flight from a hill top or some other place of considerable height if a flight of any length is to be made. Sail-flying differs from gliding in that the machine maintains or increases its elevation during flight by making use of ascending air currents, these currents carrying the plane to high altitudes.

The ascending air currents may be formed in various ways. The hot sun shining on extensive building roofs, a strip of sand, or on a plot of bare ground will cause convection currents, the hot air rising and the cooler air replacing it. Strong winds blowing in from sea form an ascending air current upon rushing up the slopes of sand dunes or upon breaking against coastal forests. One of the strongest upward air currents is the one forming cumulus clouds. The pilots of the highly sensitive sail-planes get under such a cloud and are carried along with it and carried upward by the uprising air current. This makes it possible to sail-fly even over flat country.

In learning to fly sail-planes the beginners are instructed in the use of less sensitive gliders. These machines do not respond readily to vertical air currents. The flight in them is a true glide. They are started by pulling them down hill until they reach a speed at which they are capable of sustentation. After the beginner has learned the elements of control in the glider he does his real flying in the sail-plane.

The sail-plane is launched in a different manner than the gliders. A long elastic rope is attached to the front of the sail-plane. Several men or boys draw out the rope, others holding the machine. When the plane is let go it snaps into the air as from a catapult with sufficient velocity to maintain flight. The flight will be merely a glide however, if the pilot cannot find an ascending air current to increase his altitude. The ascending air currents are invisible but an experienced pilot knows where to look for them.

Gliding is the oldest form of flying. Otto Lillienthal, Octave

Chanute, and the Wright brothers experimented with gliders before the first successful motored plane made its flight in 1903. That it is not merely a boy's pastime is shown by some of the present records established by sail-planes. A continuous flight of over 92 miles was made by Robert Kronfeld of Vienna in 1929. An altitude of 7300 feet above the starting place has been attained in a sail-plane by the same aviator. In April 1930, Barstow at San Diego, California, maintained glider flight for 15 hours and 12 minutes. How long such a flight may be maintained or how far one might go depends upon local conditions, and the skill of the pilot in making use of those conditions. Greatly increased interest in gliding in the United States promises to rank gliding and soaring with the most important outdoor sports.

Landing. — Most important is it for a flyer to know how to land; otherwise his flying knowledge is futile. The possibility of a forced landing should always be kept in mind and a pilot should endeavor to keep within gliding distance of a suitable landing place if possible.

The pilot may approach ⁸ the landing field with either a rapid or a gradual descent, with power entirely off or with engine partly throttled or running intermittently, as he judges to be best considering the initial altitude, the distance to be covered, the direction and velocity of the wind, etc. It is well to put power on occasionally in order to keep the manifold clear so that the engine will not choke if it becomes necessary to put on full throttle suddenly. Turns and spirals are made when the distance is short, but a turn should not be made near the ground as there is danger of the low wing striking the ground.

The pilot plans the approach so that when three or four hundred feet from the ground he can make a moderate glide straight to the landing place, directly into the wind if possible, with the two

⁸ A steep descent may be made by diving, or, when the pilot is familiar with his machine, by stalling. In either case the pilot should pull out into a moderate glide before acquiring too great velocity or approaching too near the ground.

wings level. He should not lose velocity and sustentation by gliding too flat, — that is, he should not “stall down”; nor should he gain excessive velocity by too steep a dive when near the ground. The relative velocity with the ground is the least when

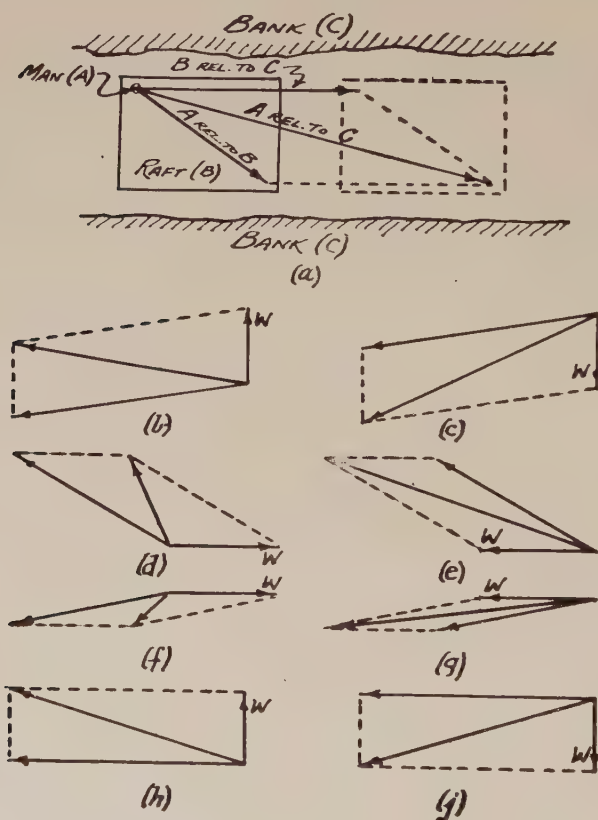


FIG. 76a. Study of relative velocities, showing effect of wind currents on flight path. In the parallelograms, the side marked W is the velocity of the wind relative to the ground, the other side is the velocity of the aircraft relative to the air, and the diagonal is the actual flight path velocity, relative to the ground. The following cases are shown: the aircraft (b) gliding in an up-current, (c) gliding in a down-current, (d) climbing into the wind, (e) climbing with the wind, (f) gliding into the wind, (g) gliding with the wind, (h) in level flight attitude in an up-current, and (j) in level flight attitude in a down-current.

a landing is made against the wind. See Fig. 76a (e). Landing with the wind or in a cross wind should be avoided; but such landings may be accomplished by an experienced pilot and are sometimes necessary.⁹

Making a landing is an art and much is left to the judgment of the pilot as to the condition of the field, length of run, etc. As he approaches the ground with a moderate glide, he levels off more and more, so that the gliding angle and velocity¹⁰ become less and the rate of descent V_c becomes less, as shown by the curve AB in Fig. 77. When a few feet from the ground the flight path becomes practically horizontal and the vertical velocity V_c becomes zero. As the machine thus glides horizontally it loses velocity and, as it begins to settle, the pilot slowly draws back the control stick, thus checking the velocity of the machine and lowering its tail before touching the ground.

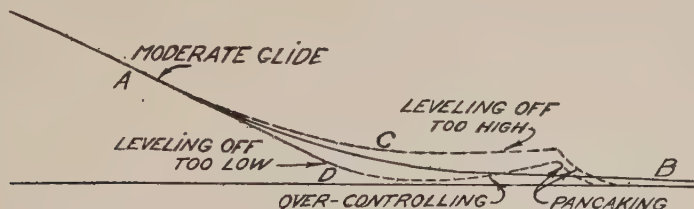


FIG. 77. In landing, the pilot levels off after a moderate glide, as shown by the curve AB , the vertical velocity being reduced as much as possible before the machine touches the ground. Curve AC shows the flight path when the pilot levels off too high; curve AD shows the flight path when he levels off too low. The vertical scale is exaggerated in the drawing.

If a pilot finds he is about to make a bad landing, he should put on all power, gain altitude and try again.

Curve AC in Fig. 77 shows a landing in which the pilot has

⁹ A cross wind tends to carry the machine sidewise as it touches the ground thus breaking the undercarriage. By side-slipping into the wind the pilot may counteract this tendency, but it requires experience and judgment.

¹⁰ *Reversible pitch propeller.* — A propeller with reversible pitch may be used as a brake when making a landing. With pitch reversed, as power is applied the negative propeller thrust retards the machine, the amount of retardation being controlled by adjusting the pitch and by changing the throttle, as in some motor boats.

leveled off too high; as the machine loses velocity, it loses sustentation and finally "pancakes" and descends to the ground with a vertical velocity V_c that may be disastrous. This may be avoided by opening the throttle and regaining speed before striking the ground. It is a common fault to glide too flat when nearing the ground.

Curve *AD* shows a landing in which the pilot has leveled off too low; then, in his effort to avoid a crash he has **over-controlled** his machine so that it rises a little instead of levelling off flat. Over-control after a steep glide is likely to occur, for the velocity acquired during the glide renders the controls over-sensitive.

A **three-point landing**, in which the tail skid touches the ground at the same time as the two wheels, is considered a good landing under most conditions. Landing with tail low, so that the tail skid touches the ground first, may throw the forward part of the machine down violently; while landing with tail high, so that the wheels first touch, may cause the machine to pitch forward and overturn. Good landings, with tail high and with tail low, are, however, made; much depends upon the nature of the field and the skill of the pilot. When taxiing to the hangar after landing, rapid turns should be avoided so as to keep the wings from striking the ground.

Rules for safe operation. — Certain general precautions must be observed to insure safety in the air, among which are the following:

1. Inspect the plane thoroughly before taking off.
2. Keep flying speed; loss of speed means loss of control. If motor starts to miss while getting out of the field, nose the plane down in a straight glide and do not attempt to turn back to the field. Most crashes are caused by trying to turn close to the ground without sufficient flying speed.
3. When conditions arise that make flying hazardous, land as soon as possible. Avoid clouds in the region of a flying field.
4. Do not rely on barometer for altitude. Learn to judge alti-

tude, especially on landings. Barometric conditions may change during cross country flights, so that even a barometer that is functioning properly may read an incorrect altitude. Moreover, the altitude of the landing place may be different from that of the starting place.

5. At all times keep machine in such position, in reference to suitable ground, that a landing can be effected. Know the flying range of the plane.

6. Avoid other planes, especially when turning. If another plane is observed to be too near, increase the distance at once. Other slip-streams, if close, may be strong enough to cause loss of control.

7. No vertical banks, steep climbing turns or zooming should be done under 300 feet.

8. All acrobacy such as loops, wing-overs, figure eights, rolls, half-rolls and spins should be completed at not less than 2000 feet.

9. Come out of steep side-slips and spirals at not less than 300 feet.

10. Avoid "hedge-hopping."

11. Landings and take-offs should be made directly into the wind when possible.

12. No spins on back or tail slides should be indulged in as they put unnecessary strain on the machine.

13. Avoid violent use of the controls.

14. All machines should land in a straight glide from 500 feet.

15. To go off the ground in a side wind, be sure to allow the machine to have flying speed before attempting to arise; then turn slightly into the wind, gain a safe altitude and then level out before attempting to turn and go with the wind.

16. If machine slides in, use more rudder or take off some of the bank or combine both.

17. If flying against the wind and you wish to turn and fly with the wind, do not make a sharp turn close to the ground.

18. In gliding for a landing, if gliding flat at a high altitude, increase the angle of glide and store up speed when approaching the ground. If gliding flat and you wish to make a turn, increase the

angle of glide and allow the machine to pick up speed, then make the turn. Glide steep rather than flat and never try to stretch a glide.

19. Motors have been known to stop during a long glide because of running same throttled too low. If use of motor is desired for landing, open throttle at intervals during glide.

20. In coming down with excess speed, level out and allow machine to skim along close to the ground. Do not attempt to force the machine on the ground with more than flying speed; the result is bouncing and ricocheting.

21. Always stop the engine and turn off the switch before leaving the cockpit to prevent accidents from the propeller.

CHAPTER IX

AIRPLANE PERFORMANCE AT DIFFERENT ALTITUDES

The performance of an airplane at high altitudes differs materially from its performance at sea level because of the decreased density of the air at high altitudes. A decrease in air density, whether it be caused by high altitude or changed local atmospheric conditions, affects the performance of the airplane propeller, the plane wings, and the engine. The changes that occur are changes in magnitudes of various quantities, not changes in principles; for the principles hold regardless of air density.

Aerodynamically there are advantages as well as disadvantages in flight at high altitude, for, although there is a decrease in sustentation in air of less density, there is a corresponding decrease in resistance. The decrease in sustentation makes a high velocity more desirable, while decrease in drag makes a high velocity more readily obtainable; aerodynamically, the higher the altitude the higher should be the velocity. (It will be shown that power required increases with altitude.)

Aerodynamic performance, however, is not the only question. The gas engine depends upon the oxygen of the air for part of its fuel supply, and the decrease in engine power at high altitudes due to the decrease in oxygen, is, unfortunately, a most serious consideration. Very desirable would be an engine developing full power ¹ at all altitudes.

The various factors affecting airplane performance at different altitudes will be separately considered.

Density of air. — Air at sea level weighs about 0.075 pounds per cubic foot; its density is, accordingly, said to be 0.075. As a

¹ This result may be obtained by **supercharging**, i.e., using mechanical means for increasing the density of the air that is supplied to the motor. See Chapter XIV.

matter of fact the density of the air changes with weather conditions, but 0.075 is often taken as a standard ² value for calculating

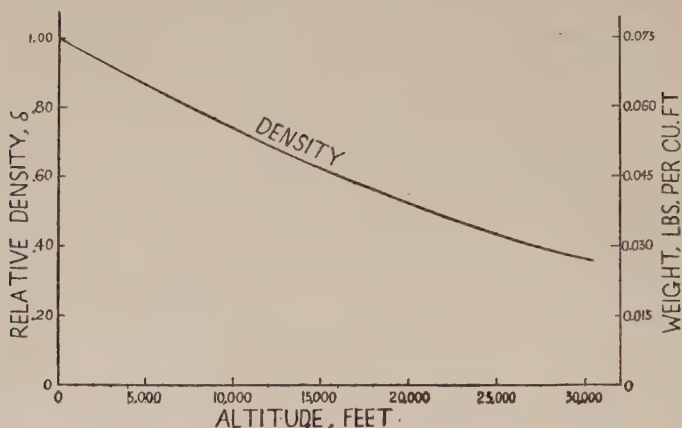


FIG. 78. Decrease of air density with altitude.

airplane performance. One cubic foot of water weighs as much as 833 cu. ft. of air; namely, 62.4 lbs.

Although air is light compared with water and other substances, it has a weight which is not inconsiderable. The weight of the air in a room 20' x 20' with a 10' height of ceiling is 300 lbs., a greater weight than a man can carry. In a class room the weight of the air may be 500 or 1000 lbs.; in a certain lecture room it is 12000 lbs.

Relative air density, δ . — In many cases we are concerned with relative rather than absolute density, the density of air at ground level being taken as 1.00. The relative density, δ , of the air at any altitude is the ratio of the density of the air at that altitude to the density of the air at ground level. The relative density at any altitude varies with weather conditions. Standard values of relative density used by the Air Service are given in the accompanying table.³ These values are also shown by the curve in Fig. 78.

² Other values are also used as standard: 0.07608, 0.0762, 0.0789, 0.0807, etc. See the following footnote.

³ For a complete tabulation of standard density ratios for altitudes up to 65,000 feet, see Report No. 218 of the National Advisory Committee for

TABLE

RELATIVE DENSITY OF AIR AT DIFFERENT ALTITUDES

Altitude Feet	Relative Density	Altitude Feet	Relative Density
0	1.000		
1,000	0.971	16,000	0.609
2,000	0.943	17,000	0.589
3,000	0.915	18,000	0.570
4,000	0.888	19,000	0.551
5,000	0.862	20,000	0.533
6,000	0.836	21,000	0.515
7,000	0.811	22,000	0.497
8,000	0.786	23,000	0.481
9,000	0.762	24,000	0.464
10,000	0.738	25,000	0.448
11,000	0.715	26,000	0.432
12,000	0.693	27,000	0.417
13,000	0.671	28,000	0.402
14,000	0.645	29,000	0.387
15,000	0.629	30,000	0.374

Lift and velocity, as affected by air density. — Sustentation is in direct proportion to relative air density δ ; thus,

$$L = \delta K_L S V^2.$$

In horizontal flight, lift is equal to weight and may be taken as constant for a particular machine; S is also constant. To get the necessary sustentation at high altitudes, it is evident that either K_L or V must be increased as δ decreases.

When a machine flies at different altitudes *at the same velocity*, the coefficient of lift K_L must be increased (by increasing the angle of attack) as the density decreases; δK_L is constant and hence $K_L \propto 1/\delta$.

Aeronautics, 1925. In the above table, at ground level the standard density is 0.07651 lbs. per cu. ft.; pressure 29.92 inches of mercury; temperature 15°C . At an altitude of 30,000 ft., standard pressure is 8.88 inches of mercury; temperature -44.44°C . The scale on the right hand of Fig. 78, has been drawn for convenience with 0.075 corresponding to $\delta = 1$.

When a machine flies at different altitudes *with the same angle of attack*, K_L remains unchanged and the velocity V must be increased as the density decreases; δV^2 is constant and hence $V \propto \sqrt{1/\delta}$. So far as sustentation is concerned, velocity should increase with altitude. Let us see whether other considerations point to the same conclusion.

At constant angle of attack, resistance remains constant when δ decreases and V increases. — The L/D ratio, at any given angle of attack, is independent of density; for

$$L = \delta K_L S V^2, \text{ and } D = \delta K_D S V^2.$$

$$L/D = K_L/K_D.$$

Since, for constant angle of attack, δV^2 is constant, the wing-resistance D is constant and is independent of density. Parasite resistance, $\delta k_s V^2$, is also constant, at constant angle of attack; for, here as before, δV^2 is constant.

It, therefore, follows that the total resistance R — the sum of wing and parasite resistance — is constant at constant angle of attack. It is to be kept in mind, however, that at constant angle

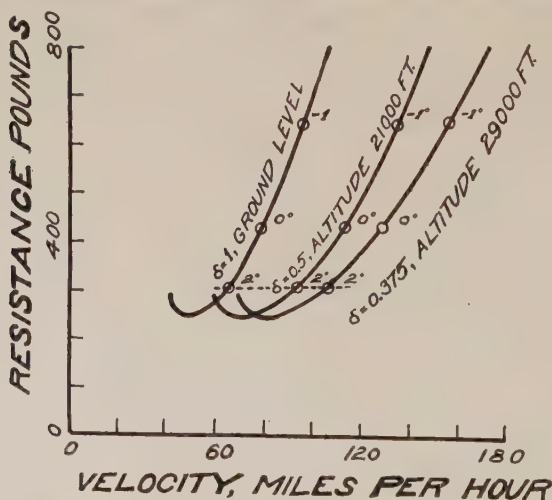


FIG. 79. Variation of airplane resistance with velocity at different altitudes. For any particular angle of attack, resistance is the same at all altitudes; velocity varies inversely as the square root of the air density.

of attack $V \propto \sqrt{1/\delta}$; the velocity necessary for sustentation is greater at higher altitudes but resistance remains the same.

When the angle of attack changes and velocity is constant, the total resistance at high altitudes may be either greater or less than at ground level; in the usual flying range it is very much less, as will be seen by the curves in Fig. 79.

The effect of change of density upon resistance is shown by the curves for total airplane resistance when $\delta = 1$ (ground level), $\delta = 0.5$ (altitude approximately 21,000 ft.) and $\delta = 0.375$ (altitude approximately 29,000 ft.). As δ decreases, any point on the curves (for example, the point corresponding to an angle of attack of 2°) is merely shifted to the right, since V varies as $\sqrt{1/\delta}$. It is interesting to note that the minimum resistance has the same value at all altitudes and is obtained at the same angle of attack but at different velocities.

Gliding. — Since the sine of the gliding angle equals R/W , it follows that, at constant angle of attack, *the gliding angle is the same at all altitudes*; the gliding velocity varies as $\sqrt{1/\delta}$. The minimum gliding angle is the same at all altitudes.

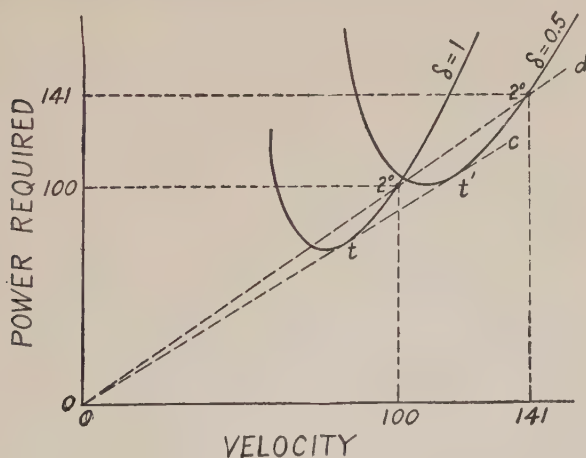


FIG. 80. Curve for power required at ground level ($\delta = 1$) and at an altitude of 21,000 ft. ($\delta = 0.5$). Power required and velocity both vary as $\sqrt{1/\delta}$, for a given angle of attack.

Power required at different altitudes. — Horse power required equals $RV/375$ and, for a constant angle of attack, varies as V or as $\sqrt{1/\delta}$, for R is constant as shown above.

Fig. 80 shows curves for power required when $\delta = 1$ (ground level) and when $\delta = 0.5$ (altitude approximately 21,000 ft.). For each angle of attack the ordinate as well as the abscissa is proportional to $\sqrt{1/\delta}$; the decrease in δ from 1 to 0.5 increases the velocity and likewise the power required for any particular angle of attack by a factor $\sqrt{2}$. Thus, in the case shown, the velocity is 100 MPH. and the power required is 100 H.P. at ground level when the angle of attack is 2° ; at an altitude of 21,000 ft. (with the same angle of attack) the velocity is 141 MPH. and the required horse power is 141 H.P.

Corresponding points, for the same angle of attack at different altitudes, lie on a straight line, as od , drawn from the origin. The points of minimum thrust, t and t' , in a like manner lie on the tangent line oc .

Power available at different altitudes. — The decrease in air density at high altitudes has much the same affect upon a gas engine as a decrease in air supply by throttling. The indicated⁴ horse-power is reduced, approximately, in proportion to the amount of air supply. With the usual gas engine, when the relative density is $\delta = 0.5$ (at an altitude of about 21,000 ft.) the air supply and the indicated⁵ horse power are only half as much as at ground

⁴ The entire power developed by the explosion of gas in the cylinders.

⁵ *Decrease in B.H.P. with altitude is greater than decrease in I.H.P. on account of losses.* — Consider, for example, an engine in which the losses are 10 H.P., delivering 100 B.H.P. at ground level. The I.H.P. is 110. When the relative density is $\delta = 0.5$ (alt. 21,000 ft.), I.H.P. = $0.5 \times 110 = 55$; B.H.P. = $55 - 10 = 45$.

It is thus seen that, for a relative density 0.5, when the indicated horse power is reduced to 50 per cent., the brake horse power is reduced to 45 per cent. of its ground level value.

If the losses were zero, the B.H.P. would be reduced the same as the I.H.P., i.e., in this case to 50 per cent. If the losses were 20 H.P., the B.H.P. in the preceding example for $\delta = 0.5$ would be only 40 % of ground value. (The I.H.P. = 120 at ground, 60 when $\delta = 0.5$; B.H.P. = $120 - 20 = 100$ at ground, $60 - 20 = 40$, when $\delta = 0.5$.)

The question of engine efficiency, although important at ground level,

level. Although this is not precise,⁶ and a variation is produced by the type of carburetor and by different secondary effects, it is sufficiently correct for the purposes of the present discussion.⁷

If the mechanical efficiency of the engine were constant, the brake horse power which the engine delivers at different altitudes would be in proportion to the indicated horse power and so in proportion to the density. As a matter of fact the mechanical efficiency is less at high altitudes, for the constant friction loss is a greater percentage of the power when the power is less.

Brake horse power, accordingly, decreases more rapidly than indicated horse power and density, as altitude is acquired; but, as

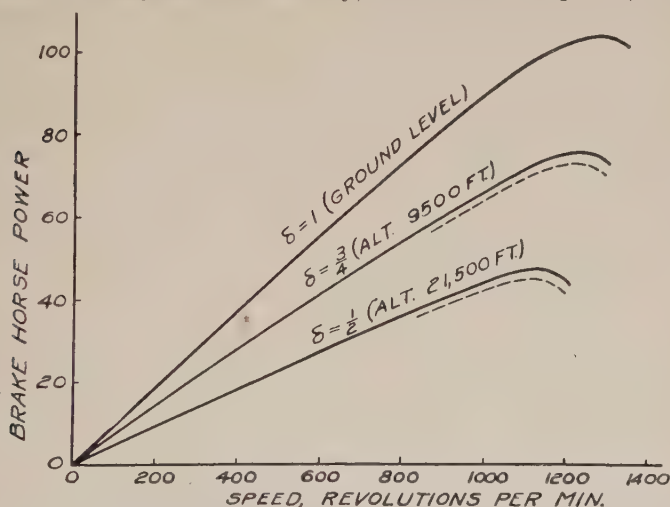


FIG. 81. Brake horse power at different altitudes. Power is less at high altitudes and varies approximately as the air density.

assumes greater importance at high altitudes; starting with a given B.H.P. at the ground, the less efficient the engine the more rapid will be the loss in B.H.P. as higher altitudes are reached.

⁶ For a more precise relationship see National Advisory Committee for Aeronautics Bulletin No. 295.

⁷ Tests on airplane engines made in an air chamber (Report No. 45, National Advisory Committee for Aeronautics) show that brake horse power is 0.71 when the density of the air corresponds to an altitude of 10,000; 0.49 for 20,000; 0.325 for 30,000, the power at ground level being 1.00. It is seen that these values are a little less than the values of δ of corresponding altitudes given in the preceding table.

an approximation, we may assume that B.H.P. varies as I.H.P., namely, in proportion to density.

Curves for brake horse power. — The solid curves in Fig. 81 show the brake horse power of a particular engine at ground level, and at altitudes of 9500 ft. and 21,000 ft., assuming that brake horse power varies in direct proportion to δ . It will be seen that the curves so drawn for $\delta = 1$, $\delta = \frac{3}{4}$, and $\delta = \frac{1}{2}$ correspond to curves for full throttle, $\frac{3}{4}$ throttle and $\frac{1}{2}$ throttle, already discussed; see Fig. 44, page 87. On account of the effect of losses, as explained above, the actual B.H.P. for $\delta = \frac{3}{4}$ and $\delta = \frac{1}{2}$ would be somewhat less, as indicated by the dotted curves.

The interesting conclusion is that the power delivered by a gas engine decreases with altitude, approximately in proportion to density. Furthermore, it is seen from the curves that the engine speed for maximum power decreases somewhat with increase in altitude.

It has already been shown to be desirable, aerodynamically, to increase velocity at high altitudes. In other words, we want to increase V while holding the engine speed N constant. But propeller efficiency depends upon the ratio V/N and is a maximum for a certain value of V/N , as was shown in Chapter VI. It is important, therefore, to ascertain whether this relation is affected by change in air density.

Operation of a propeller at different densities. — At any given value of V/N , — that is, when the angle of attack of the propeller blade is constant — propeller thrust and propeller torque vary in direct proportion to the relative air density, δ , in the same way that the lift L and drag D of an airfoil vary. Hence, thrust horse power (which is proportional to the product of thrust and V) and torque horse power (which is proportional to the product of torque and N) both vary directly as δ , when an airplane is flown at different altitudes with V and N constant.

It follows that the ratio of thrust horse power to torque horse power — that is, the efficiency of a propeller — is independent

of δ , provided the ratio V/N is constant. This is true even if V and N change provided they change in proportion, for any increase in thrust horse power, due to increase in V , is accompanied by a like increase in torque horse power, due to increase in N . Likewise, when V and N decrease, thrust horse power and torque horse power both decrease in proportion.

The efficiency of a propeller varies, therefore, as V/N , *irrespective of density*; the curves of propeller efficiency, Figs. 55 and 56, hold for all altitudes.

This means that, if we are to maintain a practically constant engine speed N as required by the engine, with a given propeller we must fly at a practically constant velocity V at all altitudes, if the propeller is to be operated near its maximum efficiency. If we fly at a higher velocity at higher altitudes, as is aerodynamically advisable, it is impossible to maintain a given engine speed N and to operate a given propeller near its maximum efficiency at all altitudes.

This, unfortunately, takes away much of the aerodynamic gain in flight at high altitudes and at high velocities; the aerodynamic gain is paid for not only by loss in engine power but also by lower propeller efficiency.

The desirability of an engine capable of delivering full power at all altitudes has already been pointed out. The advantage of a propeller operating near maximum efficiency under all conditions — that is, for different values of V/N — is likewise obvious. A glance at Fig. 56 shows how this advantage may be gained by the use of a propeller of adjustable pitch or by the substitution of one propeller for another in flight. The advantage of changing propeller pitch in flight, according to whether one desires high velocity or ability to climb, has already been pointed out; but the mechanical difficulties of changing pitch have, in the past, offset the aerodynamic advantages. These difficulties are, however, being overcome.

Curves for thrust horse power available at different altitudes. — Curves for thrust horse power available from a particular engine

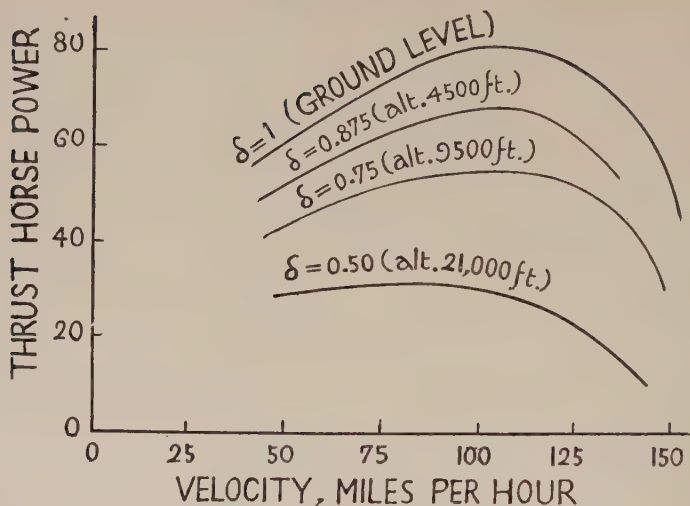


FIG. 82. Power available, or thrust horse power, from a given engine and propeller at different altitudes.

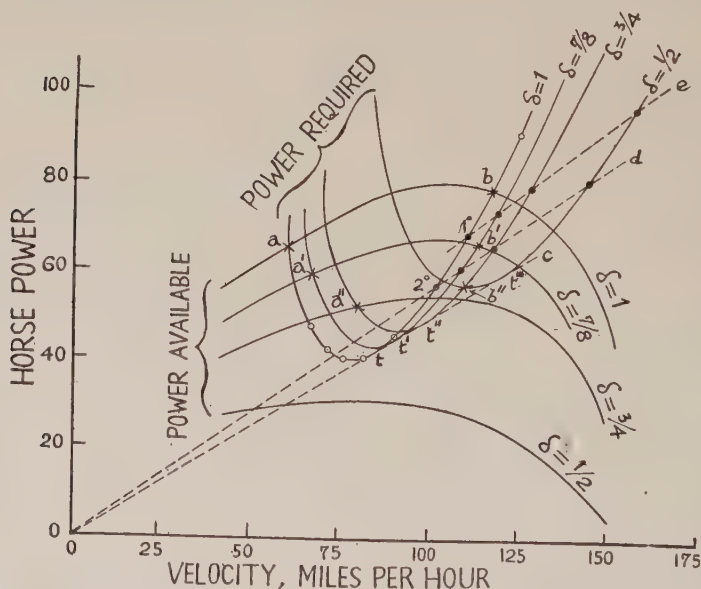


FIG. 83. Power required and power available at different altitudes (density $\delta = 1, \frac{7}{8}, \frac{3}{4}$ and $\frac{1}{2}$). Minimum velocity at a, a', a'' ; maximum velocity at b, b', b'' ; minimum thrust at t, t', t'' .

and propeller at different altitudes, on the assumption that brake horse power varies as δ , are shown in Fig. 82.

Comparison of power required and power available at different altitudes. — In Fig. 83 are drawn curves for power required and for power available at different altitudes, corresponding to $\delta = 1$, $\delta = \frac{7}{8}$, $\delta = \frac{3}{4}$ and $\delta = \frac{1}{2}$, these being similar to the curves in Figs. 80 and 82.

The points of minimum thrust, t , t' , t'' , t''' lie on the line oc tangent to the curves for power required. The line od locates the points on the curves for power required corresponding to an angle of attack of 2° ; in a like manner the line oe locates points for an angle of attack of 1° , as explained in connection with Fig. 80.

Minimum velocity is at a when $\delta = 1$; at a' when $\delta = \frac{7}{8}$, etc. Maximum velocity is at b when $\delta = 1$; at b' when $\delta = \frac{7}{8}$, etc. It is seen that as δ decreases with increase in altitude, the range between the minimum and maximum velocities becomes less.

At higher altitudes the surplus power also becomes less. When an altitude is reached at which δ has a certain value, the point of minimum and maximum velocity coincide, the curves for power required and power available being tangent, as in Fig. 64. (For the case shown in Fig. 83, this would be for a value of δ more than $\frac{1}{2}$ and less than $\frac{3}{4}$.)

This defines the "absolute ceiling," the highest altitude the machine can attain. At the absolute ceiling, the surplus power is zero; horizontal flight is possible at one velocity only, the machine losing altitude at any other velocity.

The "service ceiling" is defined as the altitude at which the rate of climb is 100 ft. per minute.

Rate of climb decreases with altitude. — In climbing, the rate of climb becomes less and less as a machine gains altitude, for the surplus power is less.⁸

⁸ This is practically true in usual machines, which are designed so as to have adequate surplus power for leaving the ground at "take off." If a machine is designed so that, at a certain altitude, the minimum power re-

Fig. 84 shows the actual climbing performance of a certain machine which reached its ceiling of approximately 21,000 ft. in about 100 minutes.⁹

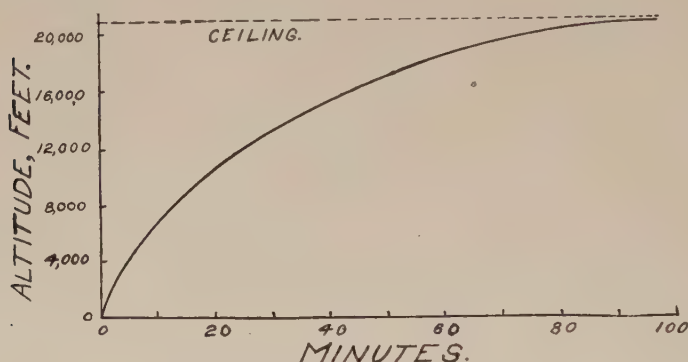


FIG. 84. Typical climbing curve.

The machine whose climbing performance is shown in Fig. 84 was not a fast climber; it reached an altitude of 10,000 ft. in about 20 minutes. This altitude is reached by better climbers in 6 or 8 minutes.

A heavy machine may have a ceiling of only a few thousand feet; other light machines, built for high altitudes, may climb to 30,000

feet. If the engine's power and maximum power available occur at the same velocity, it may have a little more surplus power at this altitude than at some lower altitudes. Furthermore, some engines cannot be operated on full throttle until a certain altitude is reached.

⁹ The climbing performance of a machine reaching a ceiling of 28,000 ft. in 70 minutes is here given by way of further illustration.

Altitude	Minutes	Rate of Climb	R.P.M.	Air Speed
0	0		1,800	
2,000	1.1	1,795	1,905	85
5,000	2.9	1,530	1,935	85
10,000	6.75	1,095	1,960	83
15,000	12.6	650	1,960	81
20,000	22.4	340		78
25,000	44.6	170		70
28,000	69.8	75		63

In this case the R.P.M. are seen to increase with altitude; in many cases they decrease slightly. Rate of climb is given in feet per min.; air speed, in miles per hr.

or 35,000 ft. An altitude of over 39,000 ft. has been attained. Still higher altitudes are likely to be reached.

In attempting altitude records the flier has his instruments sealed before the flight. On his return to earth the readings of his recording instruments are corrected for differences in temperature, etc., in a manner prescribed by the officials.

It was shown in the chapter on Power Required that the power required for an airplane was determined to a large extent by its weight. This is illustrated by Fig. 42. It is evident that the weight of the airplane also is important in determining the ceiling of the plane by determining its surplus power.

CHAPTER X

SINGLE AND MULTIPLE PLANES ¹

The total wing-area necessary for sustentation of an airplane depends upon the weight of the airplane, the characteristics of the airfoil to be used, and the speeds to be attained with the machine. This total wing-area may be obtained on a single wing, the machine then being called a *monoplane*, or on more than one wing. A cabin monoplane is shown in Fig. 84a. If two wings are used the airplane



FIG. 84a. A Curtiss Robin monoplane.

is called a *biplane*. If three wings are used the airplane is called a *triplane*. Any airplane having more than one wing may be called a *multiplane*. Whether more than one wing will be used depends

¹ This chapter, with its brief review of some of the essential elements of airplane structure, may well be read with Chapter I, or at such other time as suits the reader.

chiefly, upon structural or design features, the aerodynamic principles remaining unchanged. In like manner, whether the propeller is located in front ² as in a *tractor* or behind as in a *pusher* machine, and whether several propellers or a single one are used, are questions of design and not of principle. Whenever possible, the designer combines practical construction with aerodynamic advantages.

The relations determining sustentation, thrust, power, stability, etc., as outlined in this volume, are true for all types of airplanes. This chapter will be devoted to giving certain facts and relations which bear on airplane structure and operation, some of which are touched upon in other chapters.

Lift is largely obtained from the upper surface of a wing. — As stated in the first chapter, lift is largely obtained from the negative pressure resulting from the rarefaction of the air on the upper surface of a wing, caused by its motion relative to the air. The production of lift by the passage of air over a surface may be shown by a simple experiment with a sheet of paper held just below the mouth, as shown in position *A*, Fig. 85. As air is blown from the mouth, the sheet rises from position *A* to position *B*, due to a rarefaction above the sheet as the air passes over it. This illustrates the chief cause of lift in an airplane. It will be understood that the lift is produced by the relative motion of the surface and the air, regardless of whether it is the surface or the air that moves.

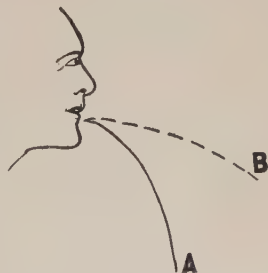


FIG. 85. Sheet is raised from *A* to *B* by blowing.

The amount of lift thus produced by rarefaction on the upper surface of an airfoil depends a great deal upon its shape. The

² The tractor is safer in that in case of a crash the heavy engine is in front of the pilot and cannot fall on him. Furthermore, on a tractor a broken propeller being in front cannot damage the fuselage or controls as it might on a pusher.

entering edge and upper surface of the airfoil are so designed that the air-stream swings up over the airfoil, as shown in Fig. 9, so as to increase the rarefaction and hence the lift. The shape of the upper surface of a wing is thus highly important, whereas the shape of the lower surface is of less consequence; indeed, a flat under-surface is almost as good as any. The air-stream as it leaves the wing is always deflected downward.

Distribution of wing pressure. — The distribution of pressure over the upper and lower surfaces of a particular wing is shown in

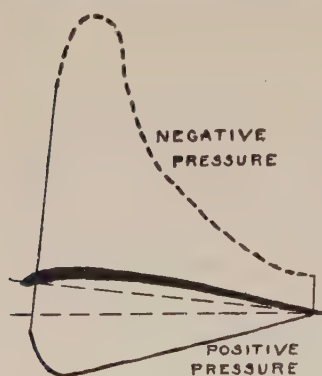


FIG. 86. Distribution of pressure on a single wing. Negative pressure on the upper surface produces more lift than the positive pressure on the lower surface.

Fig. 9a and Fig. 86. Fig. 9a shows the distribution at various positions along the span, at an angle of attack of 12° . The distribution over other sections and for other angles of attack, while different, is more or less of the same general character. Wings of different designs of course have different distributions of pressure but the type of distribution is as shown in the figure. Near the wing tips, the leakage of air around the ends decreases both the positive pressure beneath the wing and the negative pressure above it. A raked

end³ to the wing and a decrease of angle of attack near the wing tip both tend to lessen this air leakage.

It is seen: *first*, that the negative pressure above a wing is much greater than the positive pressure underneath; and *second*, that the pressure is more on the forward part⁴ of the wing than on the rear part.

³ See Fig. 108.

⁴ The center of pressure is about one-third the way back from the entering edge, its position shifting as the angle of attack is changed, as shown in Fig. 13.

The entering edge and front part of the wing are most effective in producing lift; the rear part of the wing contributes but little.

Aspect ratio. — The aspect ratio of a wing is the ratio of the square of the span to the wing-area; in the special case of a rectangular plan-form, the aspect ratio becomes the ratio of the span to the chord.

The influence of aspect ratio on lift and drag for any wing may, in large part, be understood by reflecting that the wing tips are responsible for a certain amount of leakage (which reduces lift) and for a certain amount of drag, induced by the vortices set up by the air below the wing tip swirling into the rarefied region above the wing tip. This loss of lift and generation of drag will depend on the length of the tip boundary, which is determined by the chord. For a given wing-area, the chord will decrease with an increase in aspect ratio.

Application of hydrodynamic theory has shown that the work required to overcome the induced drag is equal to the energy absorbed by the wing-tip vortices, and that the coefficient of induced drag is inversely proportional to the aspect ratio, as stated in Chapter II.

It follows, therefore, that a wing is best aerodynamically when it has a large span and small chord, that is, when it has a large aspect ratio. For structural reasons, however, the span and aspect ratio cannot well be increased beyond a certain reasonable amount. Aspect ratios from 5 to 7 (approximately the aspect of birds) are common and little is gained by using much higher values. An aspect ratio of 6 is usually taken as a standard for comparing data for various wing-sections.

The effect of change of aspect ratio upon lift and L/D ratio, for a certain wing, is shown in the following table:

CORRECTION FOR ASPECT RATIO ⁵

Aspect ratio	3	4	5	6	7	8
L	0.82	0.89	0.96	1.00	1.03	1.07
L/D	0.70	0.80	0.91	1.00	1.07	1.16

⁵ From data compiled by Lieut. W. S. Diehl, Bu. of Aero., U. S. N.

For an aspect ratio 6, the value of L is taken as unity; the value of L/D is also taken as unity. Relative values for other aspect ratios are shown in the several columns. L and L/D , determined for an aspect ratio 6, may be multiplied by the correction factors in the table to obtain the proper values for any other aspect ratio. Thus, for an aspect ratio 5, the lift is 96 per cent. and the L/D ratio is 91 per cent. of the corresponding values for an aspect ratio 6.

It is seen that little is gained in going to a higher aspect than 5, 6 or 7; on the other hand there is a considerable loss, both in L and L/D , in going to a lower aspect.

A high aspect ratio is desirable for a large lift; but for small lift, high speed and handiness in maneuvering a low aspect ratio is more suitable.

From the standpoint of longitudinal stability, a short chord (with a correspondingly high aspect ratio) is better than a long chord, for the travel of the center of pressure — a certain percentage of the chord — is then less. The shifting of the center of pressure, as the angle of attack changes, has already been shown in Fig. 13.

Biplanes and triplanes. — Wing-area is usually better obtained in a biplane or triplane than in a monoplane, particularly when large wing-area is required. This is for structural reasons. A single plane is structurally weak unless well-braced, for a spar can be no thicker than the wing itself; a single plane cannot well be built when a certain span is exceeded. When two or three planes are used, one above another, as in a biplane or triplane, the planes themselves form members of a truss and a strong structure is thus obtained; but this gain in strength is accompanied by a loss in aerodynamic efficiency.

On account of these structural advantages biplanes are commonly used, not only for large load-carrying machines but for speed machines as well. Compared with a monoplane, a multi-plane machine may have a shorter chord as well as a lesser span;

with a shorter chord there is less travel to the center of wing pressure and hence there is greater stability.

The use of more than one wing decreases the span thus reducing the storage space necessary for the machine. This is of importance from an expense standpoint since storage costs vary with the size of the machine.

On the other hand a monoplane gives more unobstructed vision to the pilot or observer and has a certain simplicity. Furthermore, for the same aspect ratio, a monoplane has a greater lift per unit area than a multiplane. This is due to the fact that the lift of multiplanes is diminished by the interference between planes, discussed in a following paragraph. The space required for storage has been reduced for some monoplanes by designs which permit folding of the wings.

In a monoplane it is desirable to have the loading as high as the structure will permit and to have the velocity high, so as to require as small a wing-area as possible; there are, however, structural limits to the possible loading.

The monoplane wing is usually strengthened by bracing; but it is to be kept in mind that all struts and wires, in monoplanes as well as in multiplanes, contribute materially to parasite resistance. Apparently there is a great future for the *internally trussed* wing, on account of its efficient operation due to elimination of parasite resistance, and reduction of ice hazard, as discussed in Chapter XVIII.

Interference between planes of a multiplane. — A multiplane, although structurally better than a monoplane, is aerodynamically inferior on account of the interference between planes.

The rarefaction or negative pressure on the top surface of a lower plane is partially neutralized by the compression or positive pressure on the under side of the plane above, so that the total lift is thus reduced. Obviously, the same air cannot be both rarefied and compressed at the same time.

In a biplane, about 55 per cent. of the lift is contributed by the upper plane and about 45 per cent. by the lower. Fig. 87 shows the distribution of pressure on the two wings of a biplane. The negative pressure on the top surface of the lower plane is much less than the corresponding negative pressure on the top surface of the upper plane, which means a decrease in lift. This decrease may be made less (1) by increasing the gap between the planes; and (2) by giving the planes a stagger so that the upper plane is in advance of the lower, as in Fig. 88.



FIG. 87. Distribution of pressure on a biplane. Negative pressure on upper surface of lower wing is much reduced by interference of the upper wing.

Biplane correction.⁶ — On account of the interference between the planes of a biplane, both lift and L/D ratio are reduced. This reduction becomes less as the gap is increased, as shown roughly by the following table from National Physical Laboratory data for an angle of attack of 6° ; little is gained, however, by making the gap greater than the chord.

CORRECTION FOR BIPLANE INTERFERENCE

Gap	0.4	0.8	1.0	1.2	1.6
L	0.61	0.76	0.81	0.86	0.89
L/D	0.75	0.79	0.81	0.84	0.88

The first line gives the gap in terms of the chord, which is taken as unity.

⁶ For more detailed information, see "Relative Lift Distribution in any Biplane," Aeronautics Bulletin No. 14, Aeronautics Branch, U. S. Dep't of Commerce.

To obtain the value of L or L/D for a biplane of any given gap, the corresponding values for a single plane are to be multiplied by the number given in the table; thus, if the gap is 1.2 times the chord, a biplane has 86 per cent. as much lift and 84 per cent. as much L/D as a monoplane, provided the biplane has *the same aspect ratio* and has *no stagger*.

A biplane may readily be given a somewhat larger aspect ratio than a monoplane (with the same area and span a biplane has twice the aspect ratio) and the increase of lift with aspect ratio may thus partially or wholly offset the decrease due to biplane interference as shown by the table in the paragraph on aspect ratio.

Interference between the planes of a biplane may be reduced by placing the upper plane slightly in advance of the lower — i.e., by a positive stagger; in this way L may be increased as much as 8 per cent., with little effect upon L/D .

Example. — As an illustration, suppose we are given $K_L = 0.00195$ for a single plane, aspect ratio 6, at 5° angle of attack, as given in the Table I. To get K_L for a biplane, aspect ratio = 7, gap = 1.2: — multiply 0.00195 by 1.03 to correct for aspect ratio, by 0.86 for biplane interference; hence, $K_L = 0.00173$. In this case, K_L for the biplane is 11.3 per cent. less than K_L for the monoplane.

Biplane construction. — Of various forms of machines, the biplane tractor is one of the most common. A good illustration of a machine of this type is shown in Fig. 98d. Biplane construction is illustrated in Fig. 88.

The distance between the two planes of a biplane is called the **gap**; this is measured as the perpendicular distance between the planes of the two chords (see glossary).

The acute angle between the wing chord and the axis of the propeller shaft is called the *angle of incidence* or *angle of wing setting*.

Stagger is determined by measuring the distance between the entering edge of the lower plane and a plumb line dropped from

the entering edge of the upper plane; this distance may be expressed in inches but is better expressed as a percentage of the

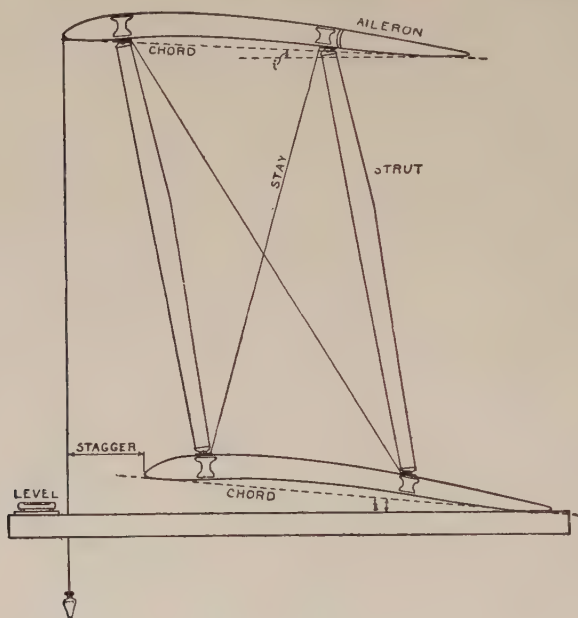


FIG. 88. Biplane construction.

chord. It is shown in Fig. 88 and Fig. 98d. Stagger is positive or negative according to whether the lower plane is behind or in advance of the upper plane. (Negative stagger is not common, but is sometimes used to obtain greater range of upward vision.)

As already mentioned a biplane — particularly when the planes are staggered — has a flatter burble point than a single plane. The stalling angle is thus reached less suddenly.

Longitudinal stability may be increased by giving the lower or rear plane of a staggered biplane slightly less ⁷ incidence than

⁷ The **decalage**, i.e., the difference in incidence between two planes is in this case said to be positive. A negative decalage is generally undesirable on account of decreased stability, but it is said in some cases to aid in increasing speed range. For "decalage," referring to incidence between main plane and tail, see paragraph on decalage, Chapter XI.

the upper or forward plane, the effect on stability being the same as giving the tail less incidence than the main plane. This is more fully discussed in the chapter on Longitudinal Stability.

Wing structure has been illustrated in Fig. 10a. The upper and lower wings of a biplane are held apart by compression members or **struts** (see Fig. 88 and Fig. 98d) fastened to the spars of the two wings. Usually, the truss formed by the two wings is strengthened by wire tension members or **stays**. Stays that are under tension in flight are termed **flying wires**; other stays, under tension when the machine is landing or has landed, are termed **landing wires**.

The understructure for carrying the weight of a machine when resting or running on the ground is termed the **landing gear** or **undercarriage** and is usually equipped with wheels (see Fig. 98d). The tail is commonly supported by a **tail skid**.

Very commonly, the lower plane of a biplane is given less span than the upper. The two planes may differ not only in size, but in shape and structure.

Effect of gap-chord ratio on distribution of load between wings of a biplane. — In order to determine where the resultant of the lifts of the two wings of a biplane acts, it is necessary to know where the center of pressure of each wing is as well as the proportion of the total lift supplied by each wing. The location of the center of pressure of each wing depends upon its angle of attack with the relative air. The proportion of the total load taken by each wing depends in part upon the gap-chord ratio. The exact proportion of the load taken by each wing depends upon the machine under consideration, but the nature of the distribution is indicated by the following summary.

(1) With positive stagger and small angles of attack the load distribution is practically independent of the gap-chord ratio.

(2) With negative stagger and small angles of attack the proportion of the load taken by the upper wing decreases with a decrease in the gap-chord ratio.

(3) At large angles of attack the load distribution is practically independent of the gap-chord ratio.

Effect of stagger on distribution of load between wings of a biplane. — As previously mentioned, interference can be somewhat compensated for by staggering the wings so the air between them does not have to try to become dense and rarefied at the same time. This staggering changes the amount of load taken by the wings, the exact proportions being dependent, as with change in gap-chord ratio, upon the machine under consideration. In general, however, an increase in positive stagger increases the load carried by the upper wing and an increase in negative stagger increases the load carried by the lower wing.

Effect of decalage on distribution of load between wings of a biplane. — A preceding paragraph mentioned that decalage affects the stability of an airplane. Change in decalage also affects the load distribution on the wings. A small negative decalage causes the lower wing to take a larger proportion of the load and a small positive decalage decreases the load taken by the lower wing.

Controls. — The controls of an airplane, illustrated in Figs. 89, 90 and 91, are three:

(1) The *rudder*, for directional or horizontal control, that is, for keeping a straight course and for turning to left or right. The rudder on an airplane acts in the same manner as the rudder on a boat.

(2) The *elevator*, for longitudinal or vertical control, that is, for keeping the flight path horizontal and for inclining it upward or downward. The elevator acts as a rudder having a horizontal axis.

(3) The *ailerons*, for lateral control, that is, for keeping the two wings on the same level and for rolling so that one wing goes up and the other down.

Rudder. — The rudder is usually operated by a foot-bar, as shown in Fig. 89, a turn to the right being made by pressing the right foot forward. (The wires in some machines are crossed, so that a turn to the right is accomplished by pressing the left foot forward; but such machines are now uncommon.)

Elevator. — The elevator is usually operated by pushing the control stick or control column (Fig. 90) forward, to lower the elevator so that the machine noses down; or backward, to raise

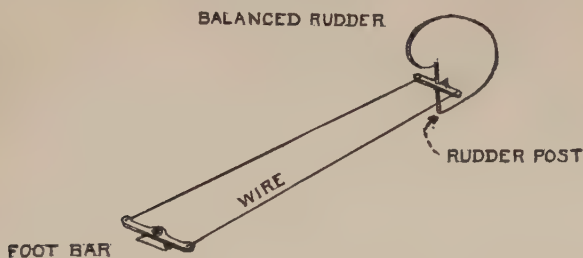


FIG. 89. Operation of rudder.

the elevator so that the machine noses up. The elevator is usually in two parts, one part being on each side of the rudder.

When a machine is banked the rudder aids in vertical control and the elevator in horizontal control. When the machine is



FIG. 90. Stick control for operating elevator. To nose down, push stick forward thus lowering elevator. To nose up, pull stick back thus raising elevator.

banked more than 45° the functions of the elevator and rudder thus become interchanged. This action is frequently referred to as *reverse control*.

Ailerons. — The control surfaces for lateral control are called ailerons; these are hinged surfaces, one (or more) on each side of the machine, and are commonly placed back of the wing near the wing tip ⁸, as shown in Fig. 91. In a biplane, the ailerons are attached to both upper and lower wings, or to the upper wing only, as shown in Fig. 88. When an aileron is turned up, the air strikes

⁸ The aileron is usually incorporated as part of the wing, as shown in Fig. 91.

its upper surface, tending to force that side of the machine down; when an aileron is turned down, the air strikes its lower surface, tending to force that side of the machine up. The ailerons are so connected that when the right one is turned up the left one is turned down, and *vice versa*.

The operation of ailerons is shown in Fig. 91. When the control stick is pushed to left or right, the corresponding side of the machine

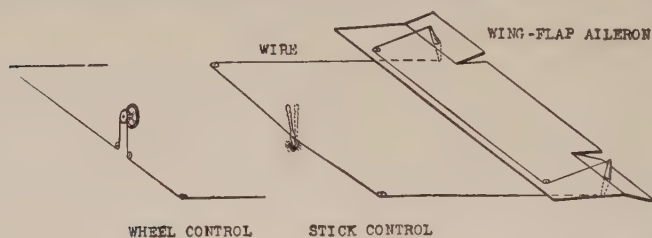


FIG. 91. Operation of ailerons for lateral control. Turning wheel or moving stick to one side causes wing to descend on that side.

is depressed by its aileron which is turned up; the other side of the machine is raised by its aileron which is turned down.

Instead of **wing-tip ailerons**, just described, **interplane ailerons**, placed midway between the upper and lower planes of a biplane are sometimes used, but interplane ailerons greatly increase resistance. The operation is the same for interplane as for wing-tip ailerons; see Fig. 110.

Wheel control. — Instead of the control stick just described, a *control wheel* as in an automobile, called a **Dep.** or **Deperdussin control**, is frequently used; the wheel is turned to the left to depress the left side of the machine and to the right to depress the right side. A control wheel is shown, in diagram, at the left of Fig. 91. (As in the case of the rudder, ailerons are sometimes connected so as to be operated by a motion opposite to the one described.)

Control surfaces. — Control surfaces for rudder, elevator or aileron are not uncommonly double convex, as in Fig. 92, but (in the case of elevator and aileron) such surfaces are often given a

section somewhat like a wing, to add to the effectiveness of their operation or to increase stability.



FIG. 92. Balanced control.

Balanced control. — A small control surface may easily be turned up or down, left or right, when it is swung from its front edge, as the aileron in Fig. 88. Large control surfaces, however, (rudder, elevator or ailerons) are frequently swung from an axis placed back from the front edge, as at *b* in Fig. 92, so as to require less force in their operation. Such control surfaces are said to be *balanced*. Note the balanced rudder in Figs. 113 and 139.

Stability. — Controls are used for directing an airplane and for maintaining it in equilibrium, that is, for giving it stability. Their action will be more fully brought out in the following chapters on longitudinal, lateral and directional stability.

CHAPTER XI

LONGITUDINAL STABILITY

To make clear the fundamentals involved we will first consider stability in general; then longitudinal stability.

STABILITY IN GENERAL

Stable, unstable and neutral equilibrium. — In order to fly, an airplane must have not only sustentation, as discussed in the first chapter, but it must also have a certain **inherent** ¹ **stability**, that is, it must be in **stable equilibrium**, so that it will automatically return to its normal position whenever it is displaced therefrom. To be sure this return may be effected in part by control by the pilot, but to depend upon such control entirely, as would be necessary if the machine itself were unstable, would indeed be precarious and would make flight a feat similar to balancing on a tight rope.

Equilibrium may be stable, unstable or neutral. A rocking chair is (within limits) in *stable* equilibrium because any slight displacement gives rise to a restoring force tending to bring it back to its normal position. An egg balanced on end is in equilibrium, but its equilibrium is *unstable* because any slight displacement will cause it to upset. A ball on a level floor is in *neutral* equilibrium; for, when it is displaced, it remains in its new position, as there is no force tending either to restore it or to displace it further.

A body, as an airplane, moving with uniform motion in a definite attitude with respect to the surrounding medium, is in stable

¹ *Mechanical Stabilizers.* — Only mention can be made of gyroscopic and other mechanical stabilizers which maintain a machine in equilibrium by automatically operating the control surfaces whenever equilibrium is disturbed. The movement of a mass due to the forces of inertia, the swing of a pendulum, the flow of mercury in a containing vessel, the pressure of the air on a small surface balanced by springs, etc., may be used to actuate the control mechanism. Gyroscopic control has, however, been most successful.

equilibrium when any displacement sets up forces that restore the original state of motion. On the other hand, its equilibrium is unstable when any displacement is accompanied by forces which cause it to depart further from its original state of motion. When slight disturbances displace a body without creating a restoring force at their conclusion, the equilibrium of the body is neutral.

A stable airplane, after any temporary disturbance, always returns to its original attitude, which is determined by the positions of its controls and the power delivered by the engine and propeller. With controls and power unchanged, an airplane is in equilibrium for one angle of attack only.

Conditions for stability. — There are two general conditions for equilibrium. To these a third is added in order that the equilibrium shall be stable: —

First. The resultant of all forces acting upon the body in question must equal zero; or, otherwise stated, the sum of the vertical forces must equal zero and the sum of the horizontal forces must equal zero.

Second. The sum of all moments tending to produce rotation of the body must equal zero.

Third. There must be a restoring moment whenever the body is displaced.

The first condition has been fully dealt with in the preceding chapters and needs no further discussion. Thus, it has been shown that, for horizontal flight, Lift = Weight (sum of vertical forces equals zero), and Thrust = Resistance (sum of horizontal forces equals zero). This condition is illustrated in Fig. 96. In gliding, it has been shown (Fig. 75) that weight is equal to the resultant of lift and resistance, that is, the resultant of all forces acting is zero.

The second and third conditions in regard to moments remain for consideration.

Moments. — An airplane rotates about its center of gravity, and every force acting upon it that does not pass through the center of gravity tends to produce rotation. The tendency of a force to

produce rotation is measured by the **moment of the force** about the center of gravity, that is, the product of the force and the perpendicular distance from the center of gravity to the line of action of the force.

When two equal forces act along parallel lines in opposite directions, they are said to produce a **couple**; the **moment of a couple** is a measure of its tendency to produce rotation and is equal to the product of either of the two forces and the perpendicular distance between them. See Figs. 97 and 98.

Three stabilities of an airplane. — Stability of an airplane may be considered under three heads:

Longitudinal or fore-and-aft stability, about a “pitching” axis which passes through the center of gravity and is perpendicular to the plane of symmetry of the machine.

Lateral stability, about a “rolling” axis, which passes through the center of gravity and is more or less in the line of flight.

Directional or “weather-cock” stability, about a “turning” or “vertical” axis, often referred to as a “yawing” axis, which passes through the center of gravity and is more or less vertical.

These stabilities are not independent, for rolling produces turning and turning produces rolling, and either may cause an airplane to change its longitudinal attitude, that is, to nose up or to nose down.

Amount of stability that is desirable depends upon intended use.

— The amount of stability that a machine should possess depends to a large extent upon the use for which it is intended. A high degree of stability decreases the sensitiveness of control and, although advantageous in many ways, is not desirable when quick maneuvers are to be made.

Indeed, for such maneuvers, lateral and directional stability may well be quite small or practically *nil*, control by the pilot being depended upon to preserve lateral equilibrium. For cross-country transport, on the other hand, such small stability would be quite inappropriate and would put upon the pilot too great a burden of

control. In no case, however, can longitudinal stability be safely so reduced.

Dynamic stability. — A body that is statically stable is not always dynamically stable. A body, which, if displaced from its normal position, oscillates back and forth through a gradually decreasing amplitude finally coming to rest at its normal position, is said to have *dynamic stability*.² It is also statically stable. Let us consider a pendulum which has been displaced from its position of rest. If the pendulum is freed and has no force except gravity and friction acting on it, it will return toward its normal position and, by reason of its inertia, pass through that position to a displacement in the opposite direction from the original displacement. It will continue to swing and, by reason of the damping action of the mechanical and air friction, will have its amplitude gradually decreased until it finally stops in a vertical position. This illustrates what is meant by dynamic stability. Dynamic stability with quick damping is desirable in airplanes.

Neutral dynamic stability. — If a force were applied to the pendulum at the end of each swing, just large enough to overcome the damping action, the pendulum would continue to swing indefinitely with the initial amplitude. It would then be said to have *neutral dynamic stability*.

Dynamic instability. — If the force of the preceding paragraph were so large that it more than overcame the damping action, the pendulum would swing with gradually increasing amplitude. The pendulum would then be *dynamically unstable*. The pendulum is evidently statically stable in all three instances because there is a restoring force to return it to its vertical position when it is displaced from that position in each instance.

² Results of tests to determine the dynamic stability of airplanes in flight are contained in the National Advisory Committee for Aeronautics Reports Nos. 162, 170, and 172.

Distribution of weight. — Concentration of weight near the center of gravity gives sensitiveness of control and is generally desirable. When weight is concentrated oscillations are quickly damped out but a machine is more sensitive to gusts; it is not desirable for a machine to be so sensitive that it follows every puff.

Distributing the weight gives less sensitive control; oscillations have a greater period and are less readily set up, but they are less easily damped and persist longer.

Weight may be distributed longitudinally and at the same time remain concentrated laterally and vertically. Such a distribution of the weight fore-and-aft will increase the moment of inertia about the pitching and the turning axes; the oscillations about these axes will thus become slower and the control less sensitive.

Damping of oscillations. — Oscillations are damped by large surfaces placed at a distance from the axis about which the oscillations take place. The damping may be so great that no oscillations take place, the return of the airplane to its original attitude after displacement being *dead beat*.

Effect of velocity upon control and stability. — The control of an airplane and likewise its stability are dependent upon air pressure on the airplane surfaces and are therefore dependent upon airplane velocity. Loss of velocity means loss of control and loss of stability. When velocity is decreased to a certain amount, the controls are somewhat "wobbly" and, as the velocity is further decreased, become entirely ineffective.

Many factors affect stability. — There are many factors that affect airplane stability and these factors have different relative importance in different machines. Some factors of general significance will be discussed, but it should be kept in mind that in certain types of machine factors not here mentioned may assume

importance. The effects here discussed are, however, typical and should give the reader a general view of the subject as a whole.

LONGITUDINAL STABILITY

A single lifting surface is unstable.³ — In order to secure large lift and relatively small resistance, a cambered plane is always used as a lifting surface. But a cambered plane is in itself unstable. This is on account of the fact that the center of pressure on such a plane shifts forward when the angle of attack is increased and backward when the angle of attack is decreased, as already discussed; see Fig. 13.

Any slight departure from the normal angle of attack, caused by a slight nosing up or a slight nosing down of the machine, is immediately augmented, on account of this shifting of the center of pressure. If the machine noses up a little, it tends to nose up more and more; if it noses down a little, it tends to nose down more and more and finally to dive. It is seen, therefore, that a single plane of suitable shape for flying is longitudinally unstable. It is true that stability might be secured by using a single flat plane, in which case the center of pressure shifts backward when the angle of attack is increased and forward when the angle of attack is decreased, as shown in Fig. 8. Stability might also be secured by using a wing of pronounced double curvature, but it would not be desirable to obtain stability in either of these ways on account of the great sacrifice in lift and the relatively large wing-resistance.

Stability is secured by an additional plane or tail. — The practical method for obtaining longitudinal stability is by

³ To demonstrate the instability of a cambered plane, as contrasted with the stability of the flat plane, the reader can perform a simple and illuminating experiment with an ordinary playing card. First, launch a flat playing card from shoulder height; the card will fall to the floor in a wabby fashion, but without overturning. Second, bend the leading edge of the card until it has a slight camber, and repeat the launching operation; it should be found that the card will now fall to the floor rotating rapidly, demonstrating its longitudinal instability.

adding a second plane or tail,⁴ usually placed behind⁵ the main plane.

The tail plane may be (1) **neutral**, in which case the air exerts no pressure upon it either up or down; it may be (2) **lifting**, when the air pressure upon it is upward; or it may be (3) **depressing**, when the air pressure is downward. A depressing tail is often referred to as a **negative tail**.

A lifting tail gives least stability; a depressing tail gives most stability and possesses other advantages discussed later.

The type of tail to be used for a particular machine depends upon the location of the center of gravity of the machine with respect to the line of pressure on the main plane.

Positive and negative pitching moments. — When the line of resultant force on a plane passes through the center of gravity of the machine, the force produces no turning moment; whereas, if the line of pressure passes behind or in front of the center of gravity, there arises a moment — called the **pitching moment** — tending to produce rotation about the pitching axis, so that the machine noses up or down.

This moment is said to be **positive** when it tends to make the machine nose up and **negative** when it tends to make the machine dive or nose down. The moment is equal to the product of the pressure and its lever arm, which in this case is the perpendicular distance from the center of gravity to the line of pressure.

This is true for any plane, whether it be main plane or tail; see Figs. 93–95. For a machine to be in equilibrium the sum of the positive moments must equal the sum of the negative moments so that no rotation will be produced.

⁴ Two methods for calculating the necessary horizontal tail area for static stability are given in National Advisory Committee for Aeronautics Report No. 293.

⁵ In practically all cases the tail is placed behind. It will be shown later that a neutral tail or a depressing tail must be placed behind the main plane in order to give stability, while a lifting tail may be placed either in front or behind. Two tails have been used, one in front and one behind. A front tail is exceedingly sensitive.

SIMPLE CASE. LONGITUDINAL STABILITY WHEN THRUST
PASSES THROUGH THE CENTER OF GRAVITY

To obtain ease in control, a machine is usually so constructed that the line of thrust passes near or through the center of gravity. For simplicity we shall first consider the longitudinal stability of a machine in which the thrust passes directly through the center of gravity.

As the machine changes attitude, thrust and weight in this case continue to act through the center of gravity; these forces, therefore, produce no restoring or upsetting moment and do not affect stability.

Furthermore, for simplicity, we shall represent the machine as consisting merely of two planes, a main plane and a tail, as shown in Figs. 93-95. The forces affecting stability may thus be reduced to two: a total force F on the main plane (the resultant of lift and resistance); and a total force f on the tail plane (also the resultant of lift and resistance).

For equilibrium, the total pitching moment must be zero. Any moment due to the main plane must, therefore, be balanced by an equal and opposite moment produced by the tail. Furthermore, for stability, when the machine is displaced the resultant moment must no longer be zero but must be a *restoring* moment to bring the machine back to its original attitude. The function of the tail is to produce this restoring moment when the machine is displaced.

There are three cases to be considered, according to whether the line of resultant pressure on the forward plane passes through the center of gravity of the machine (necessitating a neutral tail), ahead of the center of gravity (requiring a lifting tail) or back of the center of gravity (necessitating a depressing tail). These cases are discussed in the following paragraphs. The effect is most clearly shown in the diagrams by representing an airplane simply as a single forward plane and a single rear plane or tail. It is to be understood, however, that a plane may be multiple, as in a biplane or triplane, and may be cambered, although shown in the diagrams as a single flat surface. The location of the center of lift and center

of resistance for a biplane or triplane wing is determined by the location of the theoretical chord of the wing combination as described in the following paragraph.

Mean chord of an airfoil combination. — In the preceding chapter it was shown that with a biplane or a triplane the total load was distributed among the various wings. In a biplane, for example, part of the lift is obtained from the upper and part from the lower wing. From mechanics it is evident that the total or resultant lift must act at some point intermediate between the upper and lower wing in order that the moment of the resultant lift be the same as the sum of the moments of the upper and lower wing. It is sometimes convenient to consider these forces as acting on the chord of an imaginary wing between the upper and lower wings. This imaginary chord is called the mean chord of the airfoil combination. However, since the mean chord shifts in size and position with change in angle of attack, in this book the forces on the airplane will be represented by vectors acting at the center of lift, the center of drag, etc., as shown in Fig. 96.

Case I. Neutral tail. Line of resultant force on forward (main) plane passes through center of gravity. — Let us first consider the case in which the line of resultant force F on the forward (main) plane passes through the center of gravity G , when the machine is in normal flying attitude, as shown in Fig. 93. As F passes through G , the forward plane causes no turning moment.

Condition for equilibrium. — Inasmuch as the forward plane exerts no turning moment, in order that the total moments shall be zero, for equilibrium, the rear plane likewise must cause no turning moment. This is accomplished by setting the rear plane in the air-stream in the position of zero lift. All the lifting is done by the forward plane, which is, therefore, the main plane; as the rear plane exerts no lift it serves only as a tail.

Condition for stability. — When the machine is in its normal flying position, the rear plane or tail is neutral and gives rise to no pitching moment. When, however, this machine is displaced from

its normal position, the positive or negative lift of the tail creates a restoring moment. Thus, when the machine starts to nose up, it is restored to its normal position by the positive lift of the tail; and

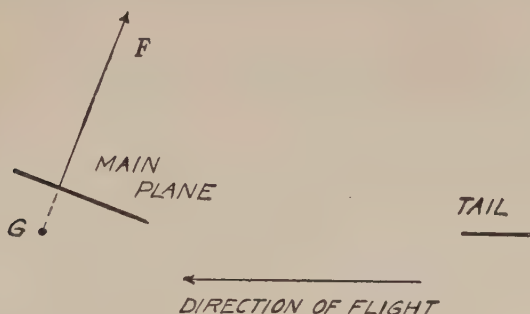


FIG. 93. Case I. Center of gravity, G , is in line of force, F , of forward (main) plane. The tail plane must be *neutral* and in the rear.

when the machine starts to nose down, it is restored to its position by the negative lift of the tail. The machine is, therefore, in *stable* equilibrium.

The magnitude of this restoring moment depends upon the force on the tail (which in turn depends upon its area and its angle of attack and velocity in relation to the air-stream) and upon the perpendicular distance between the line of this force and the center of gravity of the machine. On account of its long lever arm, the restoring moment of the tail may be made of considerable magnitude; it must always exceed any upsetting moment of the main plane which may be produced by the line of pressure of the main plane shifting forward or backward with change of angle of attack.

Relative wind for the tail. — The air-stream, as it strikes the main wings of an airplane, has an upward component with respect to the direction of the flight path, but as it leaves the wings it is deflected downward as shown in Fig. 9. This is known as downwash.⁶ The angle of attack of the tail surfaces then becomes equal to their angular setting with reference to the thrust line minus the

⁶ For a method of computing the angle of downwash see "Simple Aerodynamics" by Monteith, p. 121.

angle of downwash. The relative wind for the tail is, accordingly, not in the same direction as the relative wind for the main wings; for zero lift, therefore, a tail is inclined slightly downward toward the rear.

Furthermore, the velocity of the relative wind for the tail is greater than for the main wings, being increased perhaps 20 or 25 per cent. by the back draught or slip-stream from the propeller.

Case II. Lifting tail. Line of resultant force on forward plane passes ahead of center of gravity. — The line of resultant force F on the main plane, instead of passing through the center of gravity G , as in the case just discussed, may pass either ahead of or behind G .

When F passes ahead of G , as in Fig. 94, it gives rise to a positive moment $F \cdot x$ tending to make the machine nose up, x being the perpendicular distance of G from the line of pressure F .

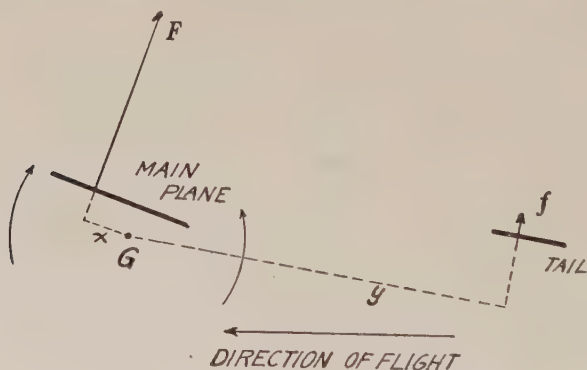


FIG. 94. Case II. Center of gravity, G , is *behind* line of force, F , of forward plane. Rear plane must be *lifting*, and is usually (but not necessarily) smaller than the forward plane.

Condition for equilibrium. — For equilibrium the positive moment $F \cdot x$ of the forward plane must be balanced by a negative moment $f \cdot y$ of the rear plane. Both planes must be lifting planes as the center of gravity is located between ⁷ the two.

⁷ With G under or back of the rear plane, a machine cannot be stable. In this case the rear plane would be the main lifting plane. The forward plane must be a neutral or depressing tail, and this would increase any displacement of the machine instead of restoring it to its original position.

If the two planes have equal lift, G is located midway between them; or $x = y$, when $F = f$, for $F \cdot x = f \cdot y$. When the lifts are not equal, G is nearer the plane with the greatest lift, which is usually (but not necessarily) the forward plane; $x < y$, when $F > f$.

Condition for stability.—Great stability cannot be obtained with a lifting tail. When the machine noses up, the lift and turning moment of both planes increase; when the machine noses down, they both decrease. Should the moments of the two planes increase or decrease at exactly the same rate, there would be no difference between the two and hence no resultant restoring moment.

To obtain a restoring moment, $f \cdot y$ must be greater than $F \cdot x$ when the machine noses up and less than $F \cdot x$ when the machine noses down. This is accomplished by making the angle of attack of the rear plane *less* than the angle of attack of the forward plane. In this case, when the machine noses up the lift and negative moment of the rear plane increase more ⁸ rapidly than the lift and positive moment of the forward plane; there is thus a resultant negative moment that restores the machine to its original position. On the other hand, when the machine noses down the lift and negative moment of the rear plane decrease more rapidly than the lift and positive moment of the forward plane, so that there is now a resultant positive moment that restores the machine.

It is thus seen that, with a lifting tail, stability is due merely to a small difference in the rate of change of lift on main plane and tail when these are set so that the tail has a smaller incidence than the main plane. With a depressing tail, on the other hand, the restoring moment when the machine is displaced from its normal attitude is more pronounced, for, as shown later, when $F \cdot x$ increases $f \cdot y$ decreases (and *vice versa*), so that the effect is additive rather than differential.

In all cases, the stabilizing effect of the tail must be greater than any tendency toward instability due to shifting of the center of pressure on the main plane. This is readily taken care of by a

⁸ It will be seen by Table I, Chapter I, that the percentage increase in lift, when the angle of attack is increased one degree, is greater for small than for large angles of attack.

powerful tail, — that is, a large tail surface placed well in the rear.

Case III. Depressing tail. Line of resultant force on forward (main) plane passes back of the center of gravity. — The line of resultant force F on the main plane passes behind the center of gravity G , at a perpendicular distance x , as shown in Fig. 95.

Condition for equilibrium. — The force F on the main plane gives

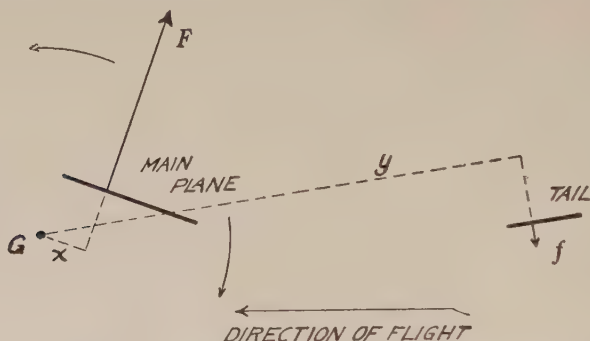


FIG. 95. Case III. Center of gravity, G , is *ahead* of line of force, F , of forward (main) plane. The tail plane must be *depressing* and in the rear.

a pitching moment $F \cdot x$ that tends to cause the machine to nose down. For equilibrium, this must be balanced by an equal and opposite tail moment $f \cdot y$ that tends to cause the machine to nose up. This is obtained by a depressing tail, for when the tail moves down the nose of the machine moves up.

Condition for stability. — It will be seen that the equilibrium is stable. When the machine starts to nose up, the lift and moment of the forward plane increase while the (negative) lift and moment of the tail decrease. A restoring moment is thus created both by the main plane and by the tail, the total restoring moment being the sum of the two, — and not the difference as in the case of the lifting tail. When the machine starts to nose down, the lift and moment of the forward plane decrease, and the (negative) lift and moment of the tail increase. Here also there is an additive restoring moment.

Longitudinal dihedral angle, or longitudinal V. — In all cases of stability, — whether with neutral, lifting, or depressing tail — it is seen that the main plane and tail are inclined with respect to each other, this inclination being sometimes referred to as decalage.⁹ It is seen, furthermore, that the two planes make a dihedral ¹⁰ angle, or V, pointing downward.

The angle between the two planes is most pronounced with a depressing tail, which as has been shown gives the greatest stability, and least pronounced with a lifting tail which gives the least stability. If the dihedral angle were inverted, making a Λ pointing upward, the machine would be unstable.

Relative advantages of lifting and depressing tail. — The only advantage in a lifting tail is that it adds to the total lift of the machine, but this addition is small and is usually not worth while in view of the greater stability and other advantages of a depressing tail.

A depressing tail is not only more stable than a lifting tail but it helps in the control of the machine as well. First, it tends to get a machine out from a nose dive, whereas a lifting tail makes it difficult to get out of one. Second, with a depressing tail the slipstream from the propeller tends to make the machine nose up when power is thrown on and to nose down to a proper gliding angle when power is thrown off. A depressing tail thus helps the operator in control; a lifting tail hinders.

A tail, therefore, is usually either depressing or neutral and is rarely lifting.

Horizontal stabilizer and elevator. — The function of a tail is two-fold, — to give stability and to give control. The entire tail may be movable, so that control is obtained by changing the angle of attack of the whole tail plane, or it may be partly fixed and partly movable.

⁹ The term "decalage" is properly used to designate the difference in incidence of the two planes of a biplane. See Glossary.

¹⁰ Called the *longitudinal* dihedral angle, to distinguish it from the *lateral* dihedral angle, discussed in the next chapter.

When the whole tail plane is movable, undue responsibility is placed on the pilot, continuous effort on his part being required in order to maintain the proper flying attitude.

Usually the tail consists of two parts: a forward fixed part, called the **horizontal stabilizer**, of proper dimensions and incidence to insure stability without effort on the part of the pilot; and a rear movable part, called the **elevator**, which is hinged to the stabilizer and is moved up or down by the pilot in his control of the machine. This is shown in Fig. 95a.



FIG. 95a. Rear view of the "Spirit of St. Louis" showing horizontal stabilizer and elevator.

The horizontal stabilizer may be set so that for certain flying conditions (for example, horizontal flight or climbing) the elevator is neutral and the machine keeps its desired attitude without effort on the part of the pilot.

The setting of the horizontal stabilizer is attended to while rigging the airplane on the ground and should always be looked to when "tuning up" a machine for flight. Frequently the horizontal stabilizer is so fixed that its adjustment may be readily changed during flight, so that the machine automatically maintains whatever attitude the pilot may desire.

An improper adjustment of the stabilizer tends to make a machine travel "nose heavy" or "tail heavy." This may be occasioned by a warping of the fuselage, by improper tension of various wires, etc. Thus, a slight displacement of the upper wing of a biplane, perhaps a drifting back due to stretching of wires, may cause a considerable lack of balance of the machine. A machine may become nose heavy or tail heavy due to a change in

the load — as by dropping bombs — in flight, and in this case an adjustable stabilizer proves useful in maintaining the proper attitude.

Tail causes machine to lie on its flight path. — Horizontal flight can only be maintained when resistance is balanced by an equal thrust. If power is cut off so that thrust is zero, resistance tends to slow down the machine so that, with decreased sustentation, it settles and thus takes an oblique path downward. Temporarily the angle of attack is thus increased. The stabilizing action of the tail [a negative (diving) moment, or — in case of a depressing tail — a decrease in the positive moment of the tail] now comes into play and makes the machine nose down until it has its normal ¹¹ angle of attack with its flight path. It may, therefore, be said that **a machine lies on its flight path** due to the stabilizing action of the tail. The ultimate gliding angle and gliding velocity are under the control of the pilot by operation of the elevator. (See gliding diagram, Fig. 75).

Similarly, when surplus power inclines the flight path upward, the tail noses the machine up.

It is seen, therefore, that the action of a tail is to cause a machine to follow its flight path, with constant attitude, as an arrow follows its course. This is the *primary* effect; there are various secondary effects.

GENERAL CASE

In the preceding discussion it is shown that for stability a tail is necessary, that in practically all cases the tail must be in the rear and that stability is greater when the tail is depressing than when it is lifting.

It is also shown that, on account of the stabilizing action of the tail, a machine tends to maintain its attitude with respect to the flight path and to nose up or down as the flight path becomes inclined up or down, that is, an airplane tends to lie on its flight path.

¹¹ A machine may oscillate before reaching steady flight conditions.

For simplicity these conclusions were derived by assuming the airplane to consist of a single main plane and a tail, and by assuming further that the thrust passes through the center of gravity and has no turning moment; but the conclusions just stated are equally true when the airplane structure is not thus limited and when the thrust passes either above or below the center of gravity.

An airplane, as a matter of fact, does not consist merely of two planes. The wings themselves may be biplane or triplane; and, furthermore, in addition to wing and control surfaces, there are many surfaces — body, struts, undercarriage, etc. Upon each of these surfaces there is an air pressure which may be considered as a single force or resolved into lift and drag components.

Four forces under consideration: lift, weight, thrust and drag. — In the case already discussed, in which it was possible to leave thrust out of consideration, it was simpler to consider the air pres-

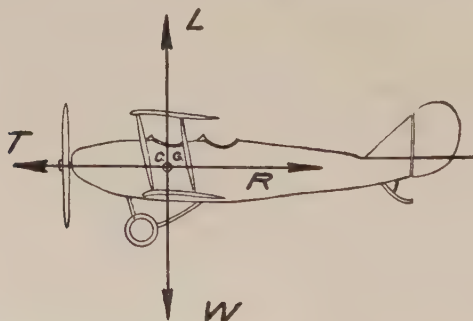


FIG. 96. In horizontal flight, lift = weight and thrust = drag. Forces are here shown as concurrent, all passing through the center of gravity. See also Figs. 97 and 98.

sures as consisting of two forces, P on the main plane and f on the tail. There are advantages in combining the lift components of all air pressures into a resultant or total lift acting through the **center** ¹²

¹² The centers of lift, drag and thrust are not points but are the lines along which the several forces act. Thus, the center of thrust is the line of the propeller shaft; the centers of lift and of drag are the lines along which the resultant lift and resultant drag act, respectively. The center of gravity, only, is a point.

of lift, and in combining the drag components into a resultant or total drag passing through the **center of drag**. The total resistance includes the drag of all the structure. The total lift is practically the sum of the lift of the wings and horizontal stabilizer, the lift on other surfaces being small and commonly neglected.

There are thus four forces affecting stability: a weight W and a total lift L equal to W ; a total drag D and a thrust ¹³ T equal to R .

Concurrent and non-concurrent forces. — When all four forces act through the center of gravity, as in Fig. 96, the forces are said to be **concurrent** or to have **coincident centers**.

In general the forces are not concurrent. Thrust may be below or above the center of gravity; and it may be above or below drag, as shown in Fig. 97. Likewise, lift may be ahead of or back of the center of gravity, as shown in Fig. 98.

There are three cases of equilibrium,¹⁴ (a), (b) and (c) as shown in Figs. 97 and 98.

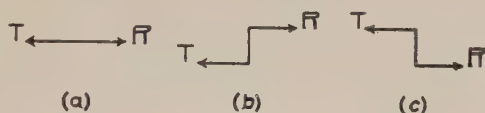


FIG. 97. Relation between thrust and drag.

(a) Thrust in line with drag. Thrust-drag couple is zero.

(b) Thrust is below drag. Thrust-drag couple is positive.

(c) Thrust is above drag. Thrust-drag couple is negative.

The thrust-drag couple must be balanced by an equal and opposite lift-weight couple. See Fig. 98.

(a) Thrust in line with drag; requires total lift to pass through center of gravity. — When thrust passes through the center of drag,

¹³ It is here assumed that thrust is in line with drag. When thrust is inclined upward it has a vertical component that supports part of the weight. See Fig. 38b.

¹⁴ Another method considering three forces, W , T , and F . — In the following pages equilibrium is studied by resolving all forces into four, namely, L , W , T and D . If L and D are combined into a single force F , namely, the total air force on the whole machine, there are three forces, W , T and F . W passes through G and has no turning moment. If t and x are the perpendicular distances, respectively, of T and F from G , the moments $T \cdot t$ and $F \cdot x$ must be equal and opposite. T is not necessarily in line with D , but may be inclined. This is a very good method of analysis but will not be followed here.

as in Fig. 97 (a), there is no drag-thrust couple. Hence, for equilibrium there must be no lift-weight couple, and lift must pass through the center of gravity G , as in Fig. 98 (a).

(b) **Thrust lower than drag; requires lift back of weight.** — When the center of thrust is lower than the center of drag, as in Figs. 97 (b), there is a positive couple that tends to make the machine nose up. This is equal to the product of thrust or drag and the distance between them and is independent ¹⁵ of the height of the center of gravity. (The height of the center of gravity has no

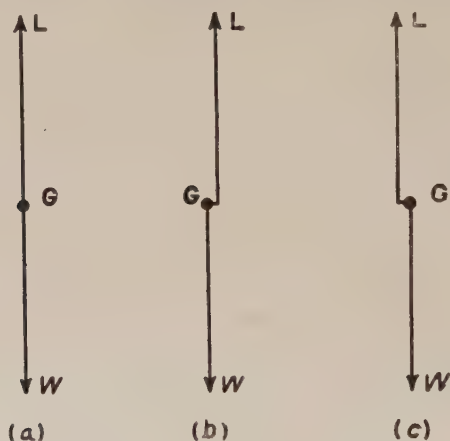


FIG. 98. Relation between lift and weight.

(a) Lift passes through G . Lift-weight couple is zero.

(b) Lift is back of G . Lift-weight couple is negative.

(c) Lift is ahead of G . Lift-weight couple is positive.

The lift-weight couple must be balanced by an equal and opposite thrust-drag couple. See Fig. 97.

effect upon equilibrium so long as steady conditions are maintained and there is no force due to acceleration. When equilibrium is disturbed, the height of the center of gravity assumes importance; see a later paragraph.)

¹⁵ The moment of T at a distance t from the center G is $T \cdot t$. The moment of D at a distance d from the center G is $D \cdot d$. The resultant moment or couple is $T \cdot t + D \cdot d = T(t + d) = D(t + d)$; it is the product of T (or D) and the distance between T and D , independent of the center G .

For equilibrium, the positive thrust-drag couple must be balanced by an equal and opposite negative couple, obtained by having lift back of weight, as in Fig. 98 (b).

In the design of a machine, the center of lift can be shifted forward or back by shifting the positions of the wings; also by adjusting the horizontal stabilizer. The center of lift may be shifted back a small amount by sweeping back the wing tips as shown in Fig. 98 (d). The position of the center of gravity can be changed by shifting the load, changing the location of seats, fuel tank, etc.



FIG. 98d. A Curtiss Falcon mail biplane with a geared Conqueror engine.

The position of the center of drag is affected by the location of the undercarriage, the radiators and the stream-lining of the various parts. The center of thrust is determined solely by the position of the propeller shaft.

(c) Thrust higher than drag; requires lift ahead of weight. — When the center of thrust is higher than the center of drag, as in Fig. 97 (c), the thrust-drag couple is negative and tends to make the machine nose down or dive. For equilibrium, this negative couple must be balanced by an equal lift-weight couple that is

positive and tends to make the machine nose up. This is accomplished by placing lift ahead of weight, as shown in Fig. 98 (c).

Distance between L and W is small compared with distance between D and T . — As lift and weight are much larger than thrust and drag, the distance between them is correspondingly smaller, in order that the couples may balance. Thus, suppose L (or W) in six times T (or D); then, in order that the lift-weight couple shall equal the thrust-drag couple, the distance between L and W must be one-sixth the distance between T and D .

Large couples undesirable. — Although balanced couples give equilibrium, whether they be large or small, it is desirable that they be small in order to avoid undue stresses in the structure. Thrust, therefore, should be not far from drag (a little below or above) and lift should be still closer to weight (a little behind or in advance of G). More commonly thrust is below drag and lift is back of weight.

Changing conditions for equilibrium. — For equilibrium in uniform flight the positive and negative turning moments are balanced in the manner already described. When changes occur in any of the forces and in their moments, there is a re-adjustment until a new state of equilibrium is reached. Thrust may be changed by change of throttle, weight by consumption of fuel or dropping of load, while drag and lift may be changed by change of angle of attack and velocity brought about by elevator control.

In the new state of equilibrium, the flight path may be horizontal or inclined, but in any case the positive and negative turning moments must be equal. As already stated, the machine tends to lie on its flight path, due to the stabilizing action of the tail. This is automatic to a certain extent, but is supplemented by the control of the pilot.

Height of center of gravity with respect to thrust. — In uniform flight, thrust is equal to drag. If thrust differs from drag, the machine changes its attitude and velocity until drag is just equal to thrust.

Any unbalanced thrust T' , equal to $T-D$, acts through the center of thrust, either forward or backward according to whether T is greater or less than D , thus giving to the machine a positive or negative acceleration. The unbalanced thrust T' and the acceleration a are both temporary.

The temporary unbalanced thrust T' gives a turning moment about G , which continues until thrust and resistance become equal, and flight is again uniform. The direction of this turning moment depends upon whether thrust passes above or below G . When thrust passes through G , a sudden change in the amount of thrust — brought about by opening or closing the throttle — will in itself cause no tendency for the machine to nose up or down, although ultimately the machine takes its new position of equilibrium as already described. When thrust does not pass through G , any change of throttle immediately tends to cause the machine nose up or down, and this may make control by the pilot easier or more difficult, according to whether it tends to swing the machine towards or away from its new position of equilibrium.

Thrust below center of gravity is desirable. — When the center of thrust is below G , an increase in thrust due to opening the throttle gives a positive moment that temporarily causes the machine to nose up; a decrease in thrust due to closing the throttle gives a negative moment that temporarily causes the machine to nose down. This is an aid to the pilot in maintaining the proper flying attitude. When power is cut off, the machine noses down and tends to assume the proper gliding angle; when normal power is again put on, the machine tends to resume its horizontal flight path and, when excess power is put on, the machine tends to climb.

With a *depressing tail*, however, the effect of the slip-stream is commonly more than enough to give the proper nosing up when power is on and nosing down when power is off; in this case, thrust below the center of gravity is *undesirable*.

Thrust above center of gravity is undesirable. — When thrust passes above G , excess thrust has a negative moment which tends to make the machine nose down when the throttle is opened and to nose up when the throttle is closed. This tendency, although

temporary, is bad, for it requires decided elevator control on the part of the pilot to counteract it. Unless thus controlled, a machine may nose up and stall when power is cut off.



FIG. 98e. An S-62 type Savoia-Machetti pusher flying boat.

This effect, however, is often more than offset by the action of the propeller slip-stream on a depressing tail.

Placing the center of gravity below the thrust can usually be avoided, but becomes necessary in some types of machines, for example, in flying boats with heavy hulls and high thrust as shown in Fig. 98e.

Stability shown by curve of moments. — The stability characteristics of a machine are well shown in a particular case by the values of its pitching moment in different attitudes. If the numerical values of the resultant moment at some particular velocity, are calculated for various angles of attack, — with a given setting of wings, horizontal stabilizer and elevator — the degree of stability of the machine becomes known. The results are well shown by curves as in Figs. 99 and 100.

For equilibrium the pitching moment must be zero at some

particular angle of attack. For stability, the pitching moment must be positive for smaller angles of attack (tending to make the machine nose up) and negative for larger angles of attack (tending to make the machine nose down) so that there will always be a restoring moment whenever the machine becomes displaced.

Curve 1, in Fig. 99, represents the pitching moment of a machine for which there is no position of equilibrium, for the pitching moment is never zero. Curve 2, shows equilibrium at a , but the machine is unstable for the pitching moment is always positive, tending to make it nose up. It is true that if the machine starts to nose down there is a restoring moment, but if it starts to nose up it continues to nose up more and more.

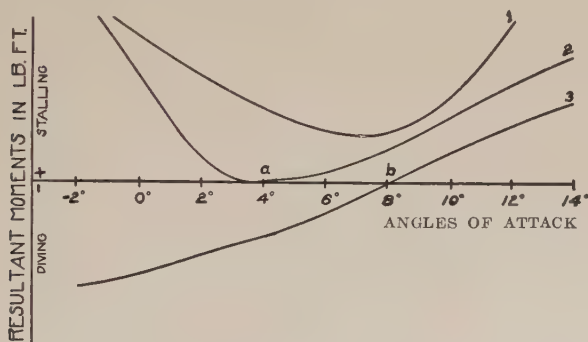


FIG. 99. Curves of pitching moment that show instability.

Curve 3 shows equilibrium at b ; but the machine is decidedly unstable, for the negative moment at small angles of attack and the positive moment at large angles is always an upsetting moment.

Stability requires that the pitching moment be positive for small and negative for large angles of attack, as shown by the curve in Fig. 100. The degree of stability is shown by the rate of increase in the restoring moment with displacement, that is, by the slope of the curve of the pitching moment.

Preferably the restoring moment should be small for a small displacement, so that the machine may rise and fall easily without being too stiff, and should rapidly increase when the displacement

becomes large. The angle of attack for zero moment should be the normal angle of attack at which the L/D ratio has about its maximum value, — say, 5° or 6° .

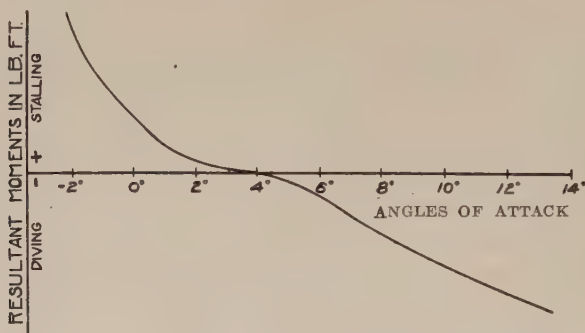


FIG. 100. Curve of pitching moment that shows stability.

The curve for moments in Fig. 100 shows equilibrium at 4° . As the machine oscillates up or down there is seen to be a small restoring moment. If the machine starts to dive, the restoring moment rapidly increases when the machine noses down more than a few degrees. This is highly desirable and tends to prevent a nose dive. For large angles of attack, on the other hand, there is not such necessity of a large restoring moment; if there is a reasonable restoring moment, the rest may be left to control by the pilot.

From the foregoing discussion it is apparent that longitudinal stability is essential to safe flying. It is secured mainly by proper size, location, and angular setting of the tail control surfaces.¹⁶ These must be determined by the designer in designing the machine. The size, location, and angular setting of the tail control surfaces are in turn determined by the weight of the plane, the location of the wings, and the location of the center of gravity with respect to the center of lift and center of resistance.

Lateral and directional stability, while important, are not so vital as longitudinal stability. Methods of obtaining these stabilities will next be discussed.

¹⁶ It is secured in the Merrill plane by shifting the wings with respect to the fuselage. See Chapter XVI.

CHAPTER XII

LATERAL STABILITY

The longitudinal or "rolling" axis of an airplane is a fore-and-aft axis in the plane of symmetry of the machine, usually parallel to the propeller axis. It passes through the center of gravity of the machine. Lateral stability is stability with reference to disturbances which tend to cause motion about the longitudinal axis, that is, any disturbance affecting the plane of symmetry of the machine. Since the position of the longitudinal axis with respect to the machine is fixed, its position with respect to the flight path varies with the angle of attack.

Although lateral and directional stability are usually mutually dependent ¹ one upon the other, rolling being accompanied by yaw or side-slipping or both, the following chapters treat these stabilities separately in an attempt to bring out clearly the factors affecting each stability. Furthermore, the discussion here given relates to normal flying conditions and not to the rapid changes of conditions encountered in acrobatic flying.

Rolling axis. — The rolling axis lies in the plane of symmetry of the machine and along its principal axis of inertia, that is, the axis



FIG. 101. Three positions of rolling axis.

along which the weight is most distributed and about which the moment of inertia is a minimum. This is the axis about which a

¹ In certain types of airplane, as the Tanager as described in Chapter XVI, rolling and yawing are independent.

machine rolls most readily. As shown in Fig. 101, the rolling axis may be either:

- A *neutral axis*, when it coincides exactly with the line of flight;
- A *raised axis*, when its forward end is raised above the line of flight (the common case); or,
- A *lowered axis*, when its forward end is lowered below the line of flight, which is not a common case.

The line of flight is always understood to be the path of the center of gravity.

Stability requires that a restoring moment be set up whenever the machine is displaced from its normal position. If the machine is rolled over to one side, with one wing raised and the other lowered, there must be a rolling moment tending to roll the machine back until the two wings are again on the same level. Although for steadiness in normal flight a certain positive lateral stability is desirable, for quick maneuvers a less positive or even an indifferent stability becomes advantageous. But in no case is it desirable to have a negative stability, which would tend to overturn the machine when once displaced from its normal position.

Neutral axis. — A machine with a neutral axis has, from symmetry, a neutral or indifferent stability, inasmuch as the angle of attack at which the air strikes the various surfaces (including keel and other surfaces as well as wings) and hence the pressure, remain unchanged, irrespective of any moderate displacement of the machine about its rolling axis. The displacement, therefore, causes little restoring or upsetting moment. With a violent displacement of the machine about its rolling axis, the resultant of the velocity of rolling and the forward velocity causes an increase in the angle of attack and lift on the lower wing with a consequent restoring moment.

When a machine rolls, however, it tends to take an oblique path downward on account of decreased lift. The flight path being thus lowered, a neutral rolling axis becomes *temporarily a raised axis*, which gives a certain positive stability as discussed later.

Inclined axis. — The conditions for stability in a machine in which the rolling axis is inclined depend upon whether the axis is raised or lowered and upon the disposition of keel surfaces and upon the shape of the wings.

Vertical surfaces as affecting lateral stability. — Important elements in lateral stability are the **vertical surfaces** which include all those areas which may be seen in a "side view" of the machine, that is, when the machine is viewed in a direction perpendicular to the plane of symmetry. These are sometimes known as **keel** surfaces. The keel surface of body, struts and other structure may in itself be sufficient, but it is frequently supplemented by a vertical stabilizer or fin so as to give a keel surface of desired size and location, — that is, either a high keel above the rolling axis or (rarely) a low keel below the rolling axis, as may be required for stability.

Small fin surfaces are sometimes placed on top of the wings, when this position suits the design of the machine, or between the



FIG. 102. Stable.

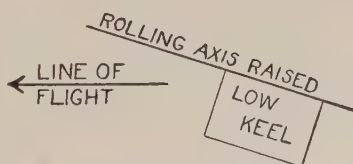


FIG. 103. Unstable.

wings of a biplane. The fin or vertical stabilizer is, however, more commonly in the rear of the machine, with the rudder hinged to its back edge, as shown in Fig. 112 of the next chapter.

Raised axis; high keel gives stability, low keel gives instability. — Place a card on a stick or wire, so as to make a flag-shaped model as in Fig. 102, and view it from in front along the line of flight; let the stick represent the rolling axis and the surface of the card represent the keel surface. When the model is thus viewed from the front (from the left in the illustration), it will be seen that with a raised axis a high keel surface is stable, for, when displaced by

rolling, one side of the keel plane is exposed to the wind (in the model, is exposed to view) and the pressure on this side is in a direction to restore the plane to its normal position. Likewise, by means of a model as Fig. 103, it will be seen that with a raised axis a low keel is unstable.

The restoring moment is seen to depend upon the position of the keel surface with respect to the rolling axis, and to be independent of its position with respect to the center of gravity, — that is, it may be above or below the center of gravity, in front of or behind it, without affecting lateral stability. (The location of the keel surface with respect to the center of gravity has, however, a direct

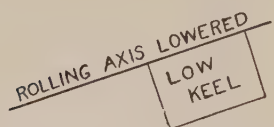


FIG. 104. Stable.



FIG. 105. Unstable.

effect on directional stability, discussed later, and on stability in gusts.)

Lowered axis; low keel gives stability, high keel gives instability. — In a like manner, it may be seen that, with a lowered rolling axis as shown in Figs. 104 and 105, a low keel gives stability and a high keel gives instability.

As the center of pressure on the keel surface is never very far from the rolling axis, the restoring moment is correspondingly small. A longer lever arm and hence a larger moment would be obtained if the keel surface were located well out on the wings, and some machines have keel surfaces so placed. The same effect, however, is practically obtained by turning the wings up so as to form a dihedral angle, as discussed below.

Effect of keel area and side-slipping. — The keel area of an airplane affects its lateral stability in a manner distinct from that just described. Consider an airplane, which by some method has been rolled over to one side as in Fig. 105a.

The component of the weight which is parallel to the wing span causes **side-slipping** of the machine, that is, motion in a direction

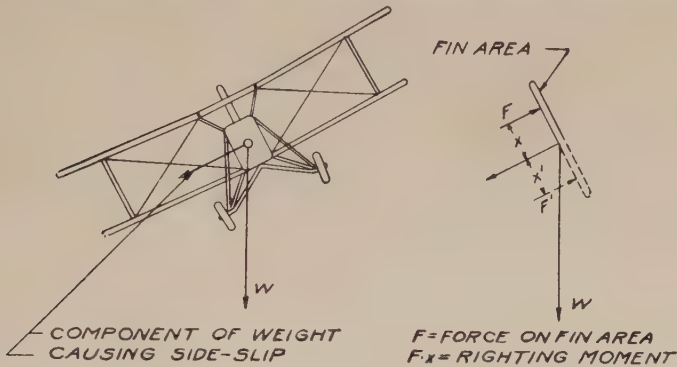


FIG. 105a. Effect of side pressure on keel area when side-slipping.

parallel to the span of the wings. The side-slipping causes an air pressure against the keel area which is proportional to the keel area and the square of the velocity parallel to the wing span. The total side pressure on the keel area acts at approximately the center of the keel area. If there is more keel area above than below the center of gravity of the airplane there will be a moment $F \cdot x$ tending to right the machine. If the center of the keel area is below the center of gravity then there is a moment $F' \cdot x'$ which tends to increase the rolling of the airplane.

It is evident then that a high keel area makes for stability in two distinct ways if the airplane has a raised axis.

Wing shape, as affecting lateral stability. — Lateral stability is materially affected if the two wings, instead of lying in a straight line, when viewed from in front, are turned up so as to form a **dihedral angle** (or V) as in Figs. 106 and 107, or are made to retreat



FIGS. 106 and 107. Dihedral angle for monoplane and biplane; front view.

as in Fig. 108, or are given a raked end as shown in the same figure. The sweep-back of the wings can be seen in Fig. 98d.

The dihedral angle (called "lateral" or "transverse" dihedral to distinguish it from the "longitudinal" dihedral angle between the main plane and tail) may be caused or noticeably increased by

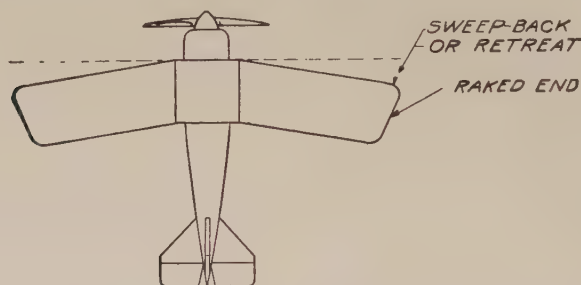


FIG. 108. Showing retreating or swept-back wings; showing also raked ends to wings. Top view.

flexure of the wings in flight. The dihedral angle often amounts to several degrees, but it may be so small (perhaps one degree or less) as to be scarcely perceptible to the eye. Up to about 8 or 10 degrees, the dihedral angle has no appreciable effect on the lift and drag characteristics of the airfoil.

Model to show effect of wing shape. — The effect of wing shape upon lateral stability depends upon the position of the rolling axis and this is best seen by inspection of a model, readily made from a small rectangular board, as in Fig. 109.

Different types of wings, made of cardboard or tin, can be inserted in the slits 1, 2 or 3 to obtain different angles of attack. The board can be rotated about the pegs *NN* for a neutral axis, about *RR* for a raised axis and about *LL* for a lowered axis. (Other pegs may be used to give other angles to these axes.)

When the model is viewed from in front along the flight path, an increase in angle of attack of left or right wing is shown by an apparent increase in its area; a decrease in angle of attack of either wing by an apparent decrease in its area. The change in

angle of attack of the raised and of the lowered wing of an airplane as it rolls is thus easily seen. It will be noted that when a machine with an inclined axis rolls, the angle of attack of one wing is increased and the other wing decreased. Let us see under what conditions this gives stability.

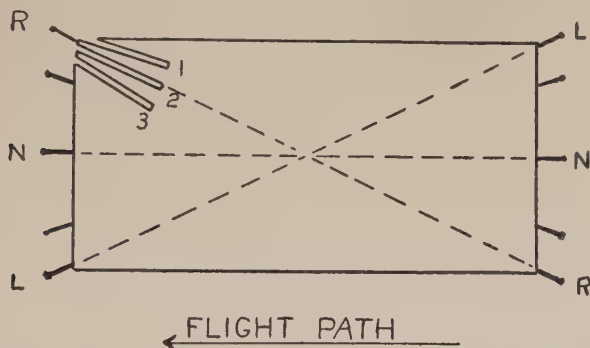


FIG. 109. Model. Wings of different forms are inserted in the slits 1, 2 and 3 and viewed from the front (from the left in the illustration) the line of sight being in the direction of the air-stream.

Lateral stability as affected by dihedral angle. — By means of a model as just described the following conclusions can be readily verified. There are four possible cases.

(1) *Dihedral angle (V) and raised axis, give stability*, because, when the machine is displaced by rolling:

Raised wing has a smaller angle of attack and hence less lift;

Lowered wing has a greater angle of attack and hence more lift.

This makes a restoring moment and it can be shown that this moment is greater as the angle of attack at which the machine is flying is greater. See note in next paragraph. Case (1) is the method actually employed for obtaining lateral stability. Cases (2), (3) and (4), although not found in practice, are, however, of interest.

(2) *Dihedral angle (V) and lowered axis, give instability*, because, when machine is displaced by rolling:

Raised wing has a larger angle of attack and hence more lift;

Lowered wing has a smaller angle of attack and hence less lift.

This makes an upsetting moment, which can be shown to be greater as the attack ² is greater.

In a like manner, it may be seen that:

(3) *Inverted dihedral (Δ) and raised axis, give instability.*

(4) *Inverted dihedral (Δ) and lowered axis, give stability.*

With the inverted dihedral, the upsetting or restoring moment is less as the angle of attack is greater. The inverted dihedral is practically never used, although machines have been so made and flown. It may be noted that a gull, when it lowers its head as it flies near the water in search of fish, also droops its wings so as to make an inverted dihedral; in this way stability is secured with what is now a lowered axis. As the head is raised again for normal flight and the rolling axis changes from a lowered axis to a neutral and then to a raised axis, the inverted dihedral (Δ) may be seen to disappear and an upright dihedral (V) to take its place.

A dihedral angle, or an inverted dihedral angle, gives a tendency for a machine to roll when struck by a side gust. Too large a dihedral angle is, accordingly, undesirable; but other means may be used for increasing lateral stability.

Straight wings. — With straight wings, that is, when there is no dihedral, the angle of attack of both wings in straight flight is always the same. Irrespective of whether the axis is raised or lowered, there is no difference in the angle of attack of the two wings when the machine is in a displaced position about its rolling axis and hence no restoring or upsetting moment due to its displaced position. However, during a violent roll, there is a restoring moment due to the velocity of roll which is compounded with the forward velocity of the wing, so that the angle of attack is increased on the lower and decreased on the upper wing.

A raised axis has a small tendency toward stability, because when the machine rolls the lowered wing moves forward and its center of pressure (which is always ahead of the middle of a plane)

² This is true for small angles of attack only, that is, for the range employed in flight in which the lift increases with angle of attack. Were the angle of attack increased beyond, say, 14° or 15° , the lift and the restoring moment would decrease.

now moves toward the wing tip, thus increasing the lever arm of the lift on this wing; the raised wing on the other hand moves backward and its center of pressure moves towards the body of the machine, thus decreasing its lever arm. There is thus a restoring moment, obtained with straight wings and a raised axis; it is much less, however, than the restoring moment obtained by using a dihedral angle.

In a similar way, a lowered axis with straight wings tends toward instability.

Retreating wings and wings with raked ends. — Retreating or swept-back wings, with a raised rolling axis, give lateral stability, for (as may be seen by inserting such wings in the model, Fig. 109), when the machine rolls, the descending wing moves forward and enters the air more squarely, with what is practically an increased aspect ratio, so as to attack more air and get more lift, thus restoring the machine to its position of equilibrium.

The effect of raked ends on lateral stability is so small as to be insignificant, although they tend to increase lateral stability slightly, as may be seen by a study of the model already described.

With a lowered axis, retreating wings and wings with raked ends would be unstable.

Retreating wings and wings with raked ends to a much less extent are thus seen to have the same effect as a dihedral angle upon lateral stability, but with the advantage that in a side gust they create no tendency for a machine to roll. It will be shown later that all three devices — dihedral angle, retreating wings and raked ends — give directional stability. But they all have the disadvantage of reducing the so-called lifting efficiency, or L/D ratio, that is, there is a decrease in the amount of lift for a given wing-resistance.

Effect of velocity on lateral stability. — All stability, depending upon the pressure of relative air upon surfaces, increases as the velocity increases.

Control. — Lateral control might well be obtained by shifting the center of gravity to left or right, but this is not done. It has been obtained by warping (that is, distorting) the planes, but lateral control is now obtained by means of auxiliary planes or *ailerons* which may be independent of the main planes (that is, between the two planes of a biplane as in Fig. 110, although this is not common) or attached to the wings as wing-flaps, as in Fig. 111. To roll the machine, the



FIG. 110. Aileron independent of main wings; not so common as the wing-flap aileron.

pilot simultaneously turns the aileron on one wing down and the other aileron up, thus giving more lift to one wing so that it rises and less lift to the other so that it descends. This movement of the ailerons is commonly effected by pushing the control stick, or by turning the control wheel, to left or to right, as illustrated in Fig. 91, page 182. The term "warping" is sometimes used to include this control by ailerons.

Banking usually aids in turning. — A machine is said to be **banked** when it is keeled over on a turn, as a bicycle rider leans inward on a curve.

When a machine is banked, the keel surface back of the center of gravity tends to turn the machine toward the lower wing and so aids in making a turn. This is due to the fact that a machine descends and side slips toward the lower wing when banked, on account of the decrease in the vertical component of the lift. (See Fig. 115 in the next chapter.) There is, accordingly, an upward and side pressure on the keel, that swings the tail up and out. In other words when a machine is banked it tends to nose down and to turn ³ *in toward the lower wing*.

There is another smaller effect that usually tends to turn the

³ This effect is often used when taxiing as an aid to the rudder in making a turn, the control stick being pushed to the *right* (instead of the left, as is usual) in making a left hand turn. The resistance of the right wing is thus decreased and the resistance of the left wing is increased. The velocity is so low that there is not enough lift on either wing to incline the machine laterally.

machine out toward the upper wing, as follows. A machine is banked on a turn by elevating one wing and depressing the other, this being accomplished by manipulating the ailerons in the manner described; but this manipulation of the ailerons will itself tend to turn the machine to one side, if the wing-resistance is thereby increased on that side and decreased on the other side. With the usual form of wing tip and aileron, this tendency is in a direction to oppose rather than aid in making a turn.



FIG. 111. Section of wing with wing flap or aileron. In (a) the wing tip and aileron normally have positive angle of attack (the usual construction); in (b) they are up-turned and have negative angle of attack (a rare construction).

If the raised wing has its resistance increased when its aileron is turned down, and the lowered wing has its resistance decreased when its aileron is turned up (as is the case with most wing sections, as *a* in Fig. 111), the raised wing will be retarded and will tend to turn the machine toward the higher (outer) wing. Such a turn⁴ is not desirable but is prevented by the rudder or by the pressure on the surface discussed above.

A turn toward the lower (inner) wing would be aided by having the wing tips (including ailerons) somewhat upturned so as to have a negative angle of attack in normal flight; see *b* in Fig. 111. The resistance of the raised wing would then be *decreased* when its aileron is swung down, and the resistance of the lower wing increased as its aileron is swung up, so that the lower wing would be retarded and would aid in making a turn toward the lower (inner) wing. The negative wing tip and aileron, although advantageous for the reasons just described, mean a sacrifice for they give less lift and greater wing-resistance, and their use is rare.

Propeller torque. — In a machine with one propeller, as the propeller rotates in one direction there is a tendency (when the power

⁴ A tendency for a machine to nose *up* on a turn is described under Secondary Effects (*d*) in the next chapter. ¹ See also footnote.

is on) for the whole machine to rotate ⁵ in the opposite direction. This may be easily corrected for in the control by the pilot, or automatically by a difference in the lift of the two wings, as described below. When flying, any correction is made by the pilot unconsciously. When starting, however, the correction may be noticeable, for the amount of correction changes as the engine accelerates; furthermore it is particularly important while near the ground to keep both wings even. When two propellers are used, rotating in opposite directions, the effects of propeller torque are neutralized. A flying boat with two propellers is shown in Fig. 145.

Automatic correction for propeller torque. — The correction for the torque of the propeller when power is on is often made automatically by a lack of symmetry in the two wings so that one wing has more lift than the other. This is sometimes done by a **droop and rise** (a droop near the end of one wing and a rise near the end of the other) and sometimes by a **wash out** on one wing (a progressive decrease in angle of attack from body to wing tip) and a **wash in** on the other wing (a progressive increase of angle of attack from body to wing tip).

A machine made in this manner is not symmetrical and has a tendency to roll when flying with the power off. While this may be counteracted by the controls when flying horizontally, it may result in a *spin* when diving. These spins cannot always be controlled. *For this reason an unsymmetrical machine is undesirable.* However, a machine made unsymmetrical to correct for the propeller torque is easier to fly with power on than a symmetrical machine. This is reversed for flight with power off.

The propeller and other rotating parts of the airplane have a gyroscopic action causing the airplane to turn sideways when nosed up or down and *vice versa*. This action is explained in the following chapter.

⁵ *Right hand engine.* — A propeller or engine is said to have right hand rotation when the rotation is clockwise as viewed along the shaft in the direction of flight. Right hand rotation of the propeller tends to cause left hand rotation of the machine as a whole (depressing the left wing and elevating the right) and this tends to turn the machine to the left.

CHAPTER XIII

DIRECTIONAL STABILITY

The preceding chapters dealt with the stability tending to make the airplane return to its normal horizontal attitude if accidentally nosed up or down and the stability tending to prevent the airplane from rolling about its longitudinal axis if its equilibrium about that axis were disturbed. These stabilities are called the longitudinal and lateral stabilities of the airplane respectively. The remaining stability is the stability which tends to make the airplane keep on a straight course, that is, it restores the machine to its path whenever it swings to the left or right. If an airplane swings sideways it is said to **yaw**. This stability which prevents yawing is known as **directional stability**. The **vertical** or **yawing axis** passed through the center of gravity of the airplane, lies in the plane of symmetry and is approximately perpendicular to the flight path.

This stability is similar to that of a weathercock and depends upon having the center of the keel surface back of the yawing axis, thus insuring a restoring moment whenever the machine departs from its course. It is to be remembered that the keel surface is all the surface seen from the side, including structure as well as auxiliary keels or fins. In some machines enough directional stability is obtained by the keel surface of the body itself, but this is usually supplemented by the addition of a small keel or vertical stabilizer in the rear. If the keel center is too far aft, side gusts will cause the machine to yaw too much.

A machine should fly straight on its flight path; but it will fail to do so and will proceed crab-fashion if there is unequal resistance on the two sides. This might be caused by unequal angle of attack of the two wings, distorted surface or camber, lack of symmetry in the tail, wrong alignment of body or fin or anything that might act as a rudder, for example the setting of struts or stream-line wires so as

to lie true in the line of flight, — points to be looked at in “tuning up” a machine.

Dihedral angle and retreating wings. — Although the keel surface is the chief element in directional stability, the wings may contribute. Directional stability is in all cases aided by retreating wings (see Fig. 98d) and by wings with a transverse dihedral angle, on account of the greater resistance of the wing which advances when the machine swings off from its course; this is independent of the location of the rolling axis. As pointed out in the preceding chapter (see Figs. 106, 107 and 108) these forms of wings likewise tend toward lateral stability, provided there is a raised rolling axis.

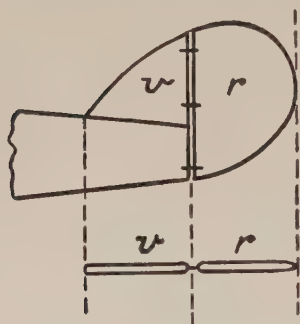


FIG. 112. Vertical stabilizer (v) and rudder (r).

On the other hand an inverted dihedral or advancing wing tips, forms of wings which are not used, would in all cases tend toward directional instability; with a lowered axis, these forms would, however, give lateral stability, as already explained.

Turning. — Turning is the deflection of the flight path to left or right. Rotation of the machine about its vertical axis, although it usually accompanies turning, is not in itself sufficient. Although turning might be effected by other means, — as by shifting the center of gravity, extending a panel on one wing to increase its resistance, etc. — it is usually effected by a rudder at the rear of the machine. This is often hinged on a vertical fin or stabilizer (already referred to in connection with lateral stability) which forms part of the keel surface; such a rudder is shown in Fig. 112. A **balanced rudder**, as in Figs. 139 and 113, reduces the force necessary for

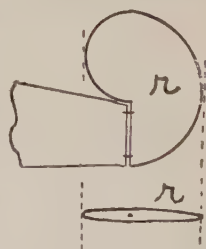


FIG. 113. Balanced rudder (r).

control and for this reason is commonly used on large machines. The rudder is usually operated by the pilot's feet, as illustrated in Fig. 89.

Turning by rudder. — A rudder alone without a keel would be ineffective, for the machine when rotated by the rudder would tend to skid along its original flight path, as does a toboggan on smooth ice. Turning control like all control depends also on a certain velocity, as in watercraft which require "steerage way" in order to answer the helm.

The relation between keel and rudder in turning is shown in Fig. 114. When the rudder is turned to one side, the pressure on the rudder causes the whole machine to rotate about its vertical axis until the rudder moment (f times its lever arm) is balanced by the keel moment (the keel force F times its lever arm); the lever arm in each case is the perpendicular distance of the force f , or F , from the vertical axis passing through the center of gravity, shown as G in the figure.

It is clear that, when the two moments are equal, the force F , with the shorter lever arm, is greater than f . The resultant of the forces F and f is a force R ,¹ deflecting the machine from its original flight path.

This deflecting force:

Increases as F increases (increasing, for a given keel moment, as the keel surface is greater and its distance from G is less);

Increases as f decreases (increasing, for a given rudder moment, as the rudder surface is smaller and further back.)

¹ The letter R here stands for *resultant*.

Strictly speaking, R is not the resultant of F and f , although for the present purpose it may be so called. More correctly, F and f may each be replaced by a couple and by a force acting at G , these two forces being shown in the figure by light dotted lines. The two couples thus formed are equal and opposite and so cancel each other. This leaves the two forces acting at G with the resultant R .

The two couples thus cancelled do not affect the motion of the airplane as a whole; they do, however, enter into strength computations.

A rudder is most effective, therefore, when it is placed far back, and when the keel surface is placed near the center of gravity.

Secondary effects. — There are important secondary effects on turning, the principal ones (see Fig. 114) being:

(a) *Turning causes banking*, for two reasons: (1) The outer wing having the higher velocity and greater lift tends to rise and the inner wing tends to descend on a turn; (2) The pressure on the keel surface on a turn tends to keel the machine over in the same direction as in (1), provided (as is usually the case) the keel center is above the rolling axis. (In some early machines, as mentioned in the preceding chapter, the rudder has been the only means for banking, no ailerons or similar devices being provided.)

(b) *Turning causes increase of resistance and loss of velocity* due to the fact that the forces F and f on keel and rudder each have a backward component.

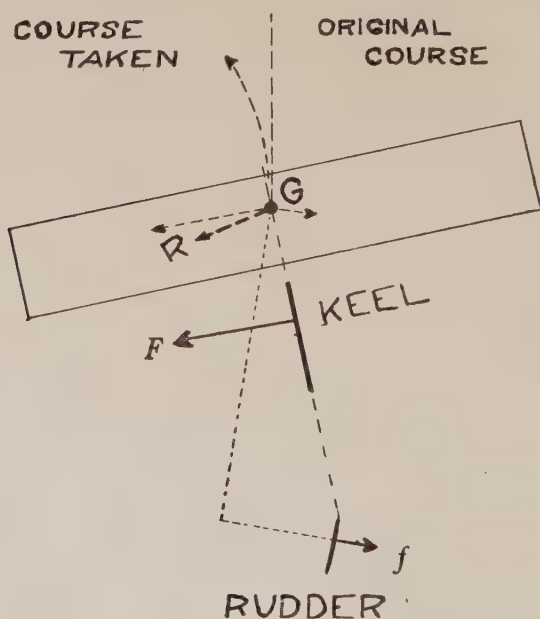


FIG. 114. Action of keel in turning.

(c) *Turning causes a decrease in lift and a tendency to descend*, that is, a tendency to stall, for two reasons: (1) On account of loss of velocity described in (b), the pressure on the wings, and hence the lift, is decreased; (2) On account of banking described in (a), the vertical component of the lift is decreased, see Fig. 115, becoming zero when a machine is banked ninety degrees.

(d) *Machine may nose up² on a turn and thus have a further tendency to stall*, if the forces F and f on keel and rudder are higher than G , on account of the backward component of these forces. Stalling may end in a tail spin.

The tendency to stall on a turn may be overcome, if necessary, by maintaining velocity either by putting on more power or by nosing down a little by means of the elevator. *Loss of velocity is to be avoided.* Obviously, to attempt to climb on a turn is dangerous unless ample reserve power is available.

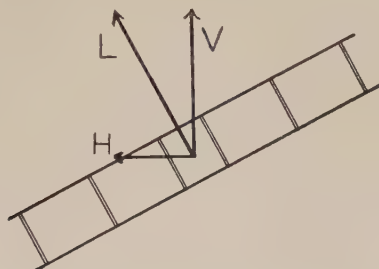


FIG. 115. Horizontal and vertical components of lift when banking. Note that lift is not vertical.

Side slipping and skidding. — If a machine is banked too much for a particular turn, it will slip *in* and *down*, on account of the horizontal component of the lift (see Fig. 115) and the decrease in the vertical component. This may result in a spin or spiral dive.

If a machine is not banked enough, it will skid *out* and (in some

² This tendency for a machine to nose up when it turns may conflict with the tendency for a machine to nose down when it banks, for a machine commonly banks and turns simultaneously. Which tendency will predominate depends upon the design of the machine, and the execution of the maneuver, — that is, the velocity at which the turn is made, the sharpness of the turn, the amount of banking, etc.

cases, due to the inertia of the machine) *up*, this being likely to happen on sharp turns and at high velocity. This may end in a stall, as the relative wind strikes the machine less from the front and more from the side and so gives less support to the machine on account of its decreased forward velocity.

Banking on a turn. — With the proper banking, the centripetal force towards the center of the turn due to banking must equal the apparent centrifugal force away from the center. There being no skidding or side slipping, the pilot will feel no side wind on either cheek. He will feel a pressure holding him to his seat with no pressure to left or right. Strings tied to guy-wires blow straight back and not at an angle. If rolling is indicated by an inclinometer³ like a level (arched upward), placed across the machine, the bubble remains central. In skidding or side slipping, the machine leaves the bubble behind; the pilot ought to keep in mind that **the control should follow the bubble**. It is a good plan to start banking just before beginning a turn.

The pilot instinctively gets the proper "feel" of a turn, as does the rider of a bicycle, without a study of moments and couples. The bicycle rider, however, usually learns by taking a few spills, — but this the air pilot cannot afford to do.

Turning by banking. — When the wings are inclined, whatever the cause, the lift on the wings has not only a vertical component but also a horizontal sideways component, as shown in Fig. 115, which tends to move the machine horizontally toward the side of the machine that is down. The flight path is thus deflected. This becomes more pronounced in machines with large keel surface. By placing large keel surfaces, both forward and aft, certain machines have been turned entirely by banking, being provided with no rudder.

Gyroscopic action. — The propeller and revolving parts of the engine form a gyroscope, so that a sudden turn of the machine side-

³ *Inclinometers.* — Various forms of inclinometers may be grouped under two heads: (1) *absolute*, that show departure from the vertical; and (2) *relative*, that show departure from the proper banking. For further description of the inclinometer see the chapter on airplane instruments.

ways will cause it to pitch or rear. Similarly any sudden pitching or rearing will cause the machine to turn to one side; for, when a sudden force is applied perpendicular to the axis of a gyroscope, the axis swings sideways at right angles to that force. The direction of this effect will depend upon the direction of rotation⁴ of the revolving parts, and so may be opposite in different machines. This effect will be but small when controls are not jerked suddenly; indeed they should not be operated suddenly on account of the severe stresses produced.

Relative values of factors affecting stability are different in different machines. — In this and the two preceding chapters a qualitative discussion is given of some of the factors that affect stability. It will be realized that the relative importance of the several factors will differ widely in different machines, that a factor negligible in one may assume importance in another, while certain characteristics of machines of one type may be entirely absent from machines of a different type. For example, in a certain maneuver one machine may automatically nose up or turn to one side; another machine in exactly the same maneuver may nose down or turn to the opposite side. General conclusions that apply to all machines are, accordingly, difficult to make. A fuller discussion, involving a study of all the factors in various types of machines, would be beyond the scope of this book. It is believed, however, that the simple analysis of certain factors here given should give the reader a clear idea of the general nature of the problem, after which he might well proceed to a detailed numerical study if interested in design.

Having considered the aerodynamics of the airplane and its propeller in the preceding chapters we will next consider the types of airplane engines, the construction of a typical airplane, and some special types of airplanes. The following chapter will discuss types of airplane engines.

⁴ With a right hand engine gyroscopic action tends to force the nose *down* when turned suddenly to the *right* (up when turned to the left); and tends to force the nose to the *right* when suddenly nosed *up* (left when nosed down).

CHAPTER XIV

AIRPLANE ENGINES

In the chapter on power available from the airplane engine, the performance characteristics of the engine alone were discussed. The purpose of this chapter is to study the elements of an internal combustion engine, the operation of the engine, and the types of airplane engines in use.

Engines used for airplanes. — The internal combustion engine is the only engine which has proven successful for aeronautic work. Steam engines and steam turbines have been tried but have been unsuccessful because of the great weight of the boiler and condenser necessary for good operation. There are two classes of internal combustion engines used for airplanes, those using *gasoline* for fuel and operating on the *constant volume* or *Otto cycle*, and those using *fuel oil* for fuel and operating on the *constant pressure* or *Diesel cycle*.

Differences between Otto and Diesel cycles. — The essential differences in the two cycles is in the manner of getting the charge of fuel and air into the cylinder, the manner of igniting it, and the pressures obtained.

In the Otto cycle, an *intimate mixture of air and atomized or vaporized fuel* is drawn into the cylinder, compressed to a moderate pressure, and ignited by means of an electric spark or hot surface. The resulting combustion is very rapid, causing an instantaneous pressure rise.

In the true Diesel cycle *pure air* is drawn into the cylinder and compressed to a pressure so high that the resulting temperature will ignite the fuel. The fuel is then injected in a fine spray by means of compressed air. The ignition of this fuel causes the air to ex-

pand, the piston moving outward on its power stroke. The combustion is relatively slow and continues until fuel admission stops resulting in a practically constant pressure expansion during that time. This period of constant pressure can, within limits, be prolonged by prolonging the admission of fuel. This cycle as described is that originated by Rudolph Diesel and is the only **true Diesel cycle**. The compression pressures attained are four to five times as great as those in the Otto cycle. Such compression pressures could not be attained in the Otto cycle operation with a high volatile fuel, where a mixture of fuel and air is compressed, as the fuel would ignite before such pressures could be reached. This is known as *pre-ignition*. It should not be confused with *detonation*, which will be discussed later.

Because of the higher pressures attained in the Diesel cycle the parts of this engine are much heavier than those of the Otto engine delivering the same power. This means that the weight per horsepower for the Diesel engine is higher than for the Otto engine.

The true Diesel engine must also have an air compressor for compressing the injection air. The pressures necessary for the injection air average about 1500 pounds per square inch.

Four strokes of the piston or two strokes of the piston may be used in getting the working substance into the cylinder; compressing it and pushing it out after it has done its work. If four strokes are needed, it is called a *four-stroke cycle*, as in the Otto or true Diesel engines. If but two strokes are needed it is called a *two-stroke cycle*.

Four-stroke cycle.—In the four-stroke cycle the charge is drawn into the cylinder through the intake valve as the piston goes from **A** to **B**, (a) Fig. 116. This stroke of the piston is known as the *suction stroke*. As the crank goes from **2** back to **1**, (b) Fig. 116, the valves are both closed and the piston compresses the charge taken in to a high pressure. This stroke is called the *compression stroke*. With the crank at about position **1**, (c) Fig. 116, ignition occurs and the expanding gases push the piston down again causing the crank to go from **1** to **2**. This is known as the

power stroke. When the piston reaches position **B**, shown at (c) Fig. 116, the exhaust valve opens and as the piston is returning to

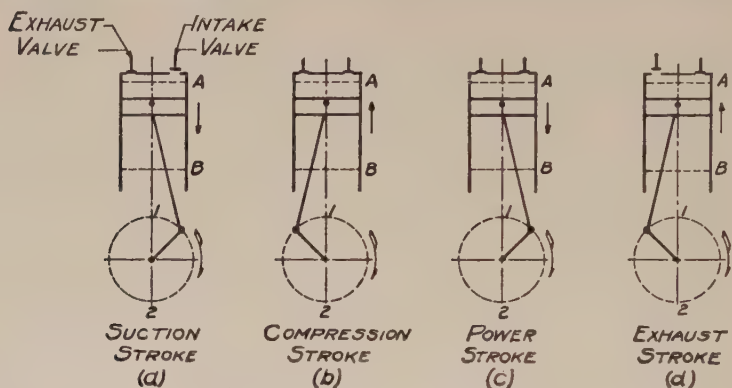


FIG. 116. Diagram to show operation of engine on four-stroke cycle.

position **A**, (d) Fig. 116, the burnt gases are forced from the cylinder. This is known as the *exhaust stroke*. The piston is then ready to begin the suction stroke and repeat the cycle. The original Otto cycle was a four-stroke cycle.

Two-stroke cycle. — In this cycle the air and fuel are forced in through the inlet valve in the cylinder head, forcing the burnt gas out through the exhaust ports which are uncovered by the

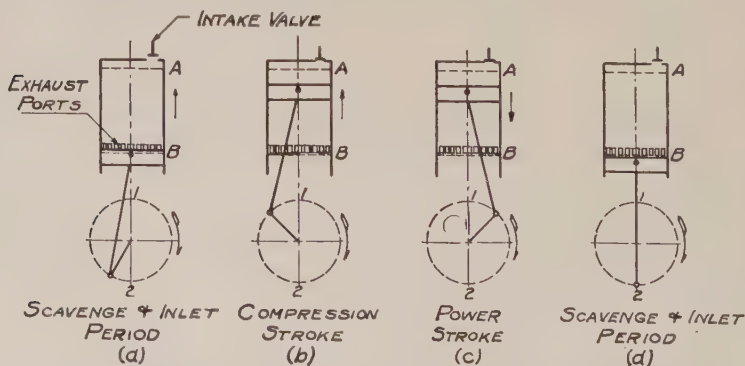


FIG. 117. Diagram to show operation of engine on two-stroke cycle.

piston, as at (a) Fig. 117. It is evident that the exhaust and intake occur simultaneously in this cycle. This period is called the *scavenging* and *inlet period*. The ascending piston covers the exhaust ports and compresses the entrapped charge to a high pressure as shown at (b) Fig. 117. Ideally, all the spent gas is forced from the cylinder and is replaced with fresh charge when the piston closes the exhaust ports. Practically, this is never attained as the turbulence caused by the inlet air causes an inter-mixture of old and new charge instead of having a sharp dividing line between the old and new charge. It is evident that some of the fresh charge of air and fuel must go out the exhaust ports before they are closed. This causes the two-stroke cycle to use slightly more fuel for the power developed than does the four-stroke cycle.

As the piston reaches the top of its stroke at the end of the compression period the charge is ignited by the spark plug as in the four-stroke cycle. The high temperature causes the gases to expand, forcing the piston down in what is known as the *power stroke* as shown at (c), Fig. 117. When the piston reaches the end of this stroke the exhaust ports are again uncovered, the intake valve opens and the scavenging and inlet period is ready to be repeated.

The two-stroke cycle is sometimes called the Clerk cycle, although internal combustion engines operating on the two-stroke cycle are also referred to as being of the Otto type. Almost all of the present airplane engines operate on the four-stroke Otto cycle. For this reason the four-stroke cycle engine will be the only type considered in detail. We will next consider the elements necessary for a simple engine operating on the four-stroke Otto cycle.

Elements of a simple four-stroke Otto cycle engine. — The elements of a simple four-stroke Otto cycle engine are shown in Fig. 118. The air and fuel are first taken into a metering device known as a *carburetor*. Here the air and fuel are mixed together in the right proportions for combustion preparatory to entering the cylinder. The mixture of fuel and air, called *charge*, is distributed

to the different cylinders of the engine by pipes running from the carburetor. This arrangement of pipes is called the *intake manifold*. Its purpose is to deliver to each cylinder an equal amount

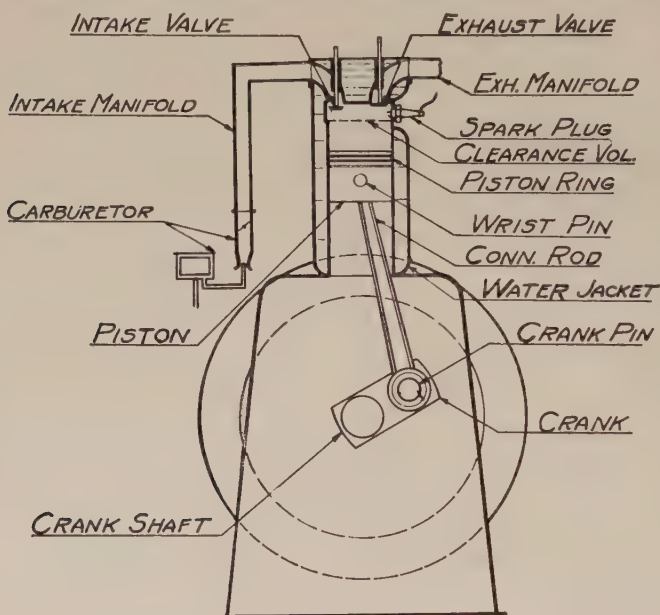


FIG. 118. Diagram of a water-cooled, four-stroke cycle engine.

of charge, having the same proportions of air and fuel as when it left the carburetor. The charge enters the cylinder through the *intake port* which is controlled by the *intake valve*. The intake valve itself is operated by a *cam*, carried on a *cam-shaft* which is geared to the *crank-shaft*.

The fuel is ignited by means of a *spark plug*, across the tips of which jumps an electric spark. After expanding, the burnt gas goes out through the *exhaust manifold*. The exhaust manifold is a piping arrangement which collects the burnt gas from all the cylinders and delivers it to the *muffler*. The purpose of the muffler is to slow the exhausted gas down to reduce the exhaust noise. Mufflers are seldom used on airplane engines because of the added weight and complication in design.

The *cylinder* itself is a short cylinder of cast iron or steel inside of which reciprocates the *piston*. The reciprocating motion of the piston is transformed into rotational motion of the crank-shaft by means of the *connecting-rod* and *crank*. The connecting-rod is connected to the piston by means of the *piston-pin* or *wrist-pin* and to the crank by means of the *crank-pin*. Thus one end of the connecting-rod travels in a straight line and the other end in a circle. The cylinder is supported by the *crank-case*. The crank-case also houses the crank-shaft, the lower end of the connecting-rods, and sometimes the cam-shaft. Frequently, with its cover called the oil pan, it is used as an oil sump or reservoir.

The pistons are grooved. The grooves are fitted with rings called *piston-rings*. These rings serve three purposes. They seal the cylinder against loss of compression. They keep the oil from the crank-case from working up into the cylinders. The oil forms a seal around the rings preventing the gas from the combustion chamber from leaking down into the crank-case. The *combustion chamber* is the part of the cylinder above the piston when it is at the top of its stroke. It is also called the *clearance volume*. The cylinder is sometimes surrounded by a jacket of water for cooling. This jacket is called the *water-jacket* and the engine is said to be *water-cooled*. Other engines have *fins* of metal around the cylinders giving them a large radiating area. Air is circulated over these fins for cooling. Such an engine is said to be *air-cooled*.

Definitions. — The total travel of the piston from its top to its bottom position is called the *stroke* of the engine. It is evident that this is twice the crank length. The total volume swept through by the piston during a complete stroke is called the *piston displacement*. This is equal to the product of piston area and stroke. The *engine displacement* is equal to the product of piston displacement and number of cylinders. A graphical record of the pressure-volume relations in a cylinder for a complete cycle is called an *indicator card*. When the piston is nearest the cylinder head of the engine, the crank is said to be at *head-end dead-center*. When the piston is farthest from the cylinder head the crank is said to be at

crank-end dead-center. The ratio of displacement plus clearance volume to clearance volume is called the *compression ratio*.

Ideal Otto cycle indicator card. — The indicator card that would be obtained from an ideal four-stroke Otto cycle engine cylinder is represented in Fig. 119. As the piston moves toward the crank-end dead-center on the suction stroke a charge of air and fuel is drawn into the cylinder at atmospheric pressure as shown by the line 1-2. The intake valve closes when the piston is at 2 and the charge is compressed to a high pressure, as shown by the line 2-3, as the piston returns to the head-end. Ignition takes place when the piston is at 3. There is an instantaneous pressure rise caused by the heating of the gases as shown by line 3-4. This occurs at constant volume, it being from this that the cycle derived its name.

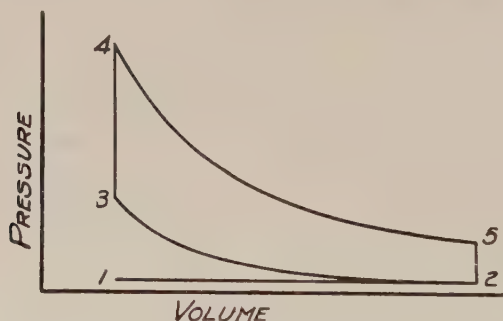


FIG. 119. Ideal Otto cycle indicator card.

The high pressure causes the piston to move toward the crank-end on its power stroke. The gases expand causing the pressure at any piston position to be represented by line 4-5. When the piston is at 5 the exhaust valve opens, the pressure drops instantaneously as shown by line 5-2. The spent charge is forced out at atmospheric pressure as shown by line 2-1.

Actual Otto cycle indicator card. — The card obtained from an actual four-stroke Otto cycle engine differs from the ideal card in the manner shown in Fig. 120. A pressure difference is required

for flow of the charge to and from the cylinder. For this reason the pressure in the cylinder during the suction stroke is below atmospheric pressure as shown by line 1-2, Fig. 120. Because the compression of the charge starts at a pressure lower than in the ideal engine, the compression line 2-3 as a whole will be lower than the compression line for the ideal engine. It has been found that if the intake valve is left open for a short time after the piston starts

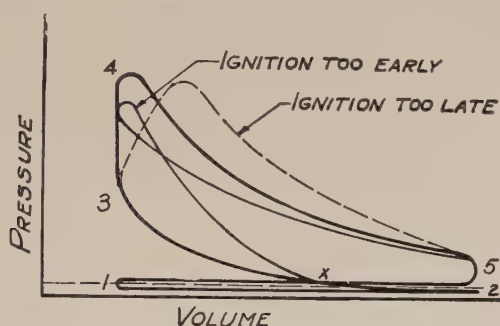


FIG. 120. Actual Otto cycle indicator card.

on the compression stroke, the inertia of the charge which is flowing into the cylinder causes it to keep flowing in the cylinder even after the piston motion is reversed. This is especially true when the engine is operated at high speed. It is known as the “**ramming effect.**” It causes more charge to be taken into the cylinder than would be taken in if the intake valve were closed at the end of the suction stroke. Since the output of the engine is proportional to the weight of the charge taken in per cycle, it is advantageous to have the intake valve close after the compression stroke begins. It is timed this way in nearly all engines.

Ignition and combustion cannot take place instantaneously as is assumed for the ideal engine. Since ignition and combustion require appreciable time and since the piston cannot linger at the end of its stroke, it is necessary that either all or part of the pressure rise should occur after the piston reaches the head-end of its stroke. If all of the pressure rise occurs after the piston has reached the end of its stroke the piston will have traveled back toward the crank-

end a considerable distance before the pressure rise is completed, with an indicator card as shown by the dotted lines in Fig. 120. If ignition occurs too early, the maximum pressure will occur before the piston reaches the head-end of its stroke, as shown by the light lines in Fig. 120. Experiments indicate that the largest indicator card area and therefore maximum power is obtained when one half the pressure rise occurs before head-end dead-center is reached, and one half after this position is reached. The card obtained from an engine, with ignition timed in such a manner, is represented by the heavy lines in Fig. 120. The top of the indicator card is rounded off considerably as at **4**. The angular displacement of the crank from head-end dead-center position, when ignition occurs, is called the *angle of spark advance*.

The burnt gas cannot be discharged instantaneously from the exhaust port when it is opened. Consequently the valve is opened slightly before the piston reaches the crank-end of its stroke. The pressure starts to drop off, causing the toe of the card to be rounded as at **5**, Fig. 120. In order to force the burnt gas from the cylinder, it is necessary that the pressure in the cylinder during the discharge stroke be slightly above atmospheric pressure as shown by line **5-1**. The exhaust valve closes at **1** with the pressure of the gas in the cylinder slightly above atmospheric pressure. As the piston starts back on the suction stroke the pressure drops to slightly below atmospheric, rounding the discharge line **5-1** into the suction line **1-2**. Thus it is seen that the actual indicator card varies from the ideal in several respects.

Significance of the indicator card areas. — The area of each loop of an indicator card represents, to some scale, the amount of work done in the cylinder while that loop is being made. On Fig. 120, the loop **5-1-2-5** represents the pump work, or work done by the piston in getting the charge in and out of the cylinder. It will be noted that this work is a loss that cannot be avoided in the actual engine because of the pressure difference necessary for the flow of the charge to and from the cylinder. In the ideal engine, where it was assumed that the charge could be drawn in and exhausted at

atmospheric pressure, the top and the bottom lines of the loop coincided, forming one line, and the pump work was zero.

The loop 2-3-4-5-2 of Fig. 120 represents, to the proper scale, the useful work done by the expanding gases on the piston. It will be noted that the triangular area 2-x-5-2 occurs on both the pump work loop and the useful work loop. Since this area is not completely enclosed it is often neglected, the pump work being taken as area 2-x-1-2 and the useful work as x-3-4-5-x. A moment's consideration will show that this is not strictly true, although the numerical result for the net useful work would be the same whether area 2-x-1-2 were subtracted from area x-3-4-5-x or whether area 5-1-2-5 were subtracted from area 2-3-4-5-2. In analyzing the performance of an engine by means of indicator cards it is particularly useful to consider the pump work as area 5-2-1-5 and the useful work as area 2-3-4-5-2 since these areas can be easily expressed one in terms of the other.

Mechanical efficiency. — The amount of work done by the gases in the cylinder can be determined by the area of the indicator card as explained in the preceding paragraph. The power expended by the gases in the engine cylinders may be determined from the indicator card areas, the piston areas, the number of cylinders, and the engine speed.

The mean effective pressure in the cylinder for the working stroke may be found by dividing the difference between the useful work and pump work areas of the indicator card by the indicator card length and multiplying the quotient by the spring scale of the indicator used in taking the indicator cards.

The horse power then may be computed from the following equation,

$$\text{H.P.} = \frac{\text{PLAN}}{33000}$$

P is the mean effective pressure in lbs. per sq. in.

L is the stroke of the engine in feet.

A is the piston area in sq. in.

N is the number of power strokes per minute for the complete engine and equals the product of the R.P.M. and one-half the number of cylinders for a four-stroke cycle engine.

The horse power obtained in this manner is called the *indicated horse power* and is designated by *I.H.P.*

The output horse power of the engine is less than the *I.H.P.* by the amount of friction loss. The output horse power is called the *brake horse power*, as it is usually measured by some sort of brake or dynamometer.¹ It is designated by *B.H.P.* The amount of power lost by friction is called the *friction horse power* and is designated by *F.H.P.*

The ratio of *B.H.P.* to *I.H.P.* is called the *mechanical efficiency* of the engine. It is designated by *M. Eff.* The mechanical efficiency is increased by anything which will increase the ratio of brake to indicated horse power. Increased engine temperature increases the brake horse power, for the same indicated horse power, because the decrease in the oil viscosity at the higher temperature decreases the friction loss.

The mechanical efficiency increases with both load and speed up to a certain point because at higher loads the friction loss, which remains fairly constant, is then a smaller percentage of the total work done in the cylinders.

Function of the carburetor. — A carburetor is essentially a device for metering fuel and air to the engine in the proper proportions and in the proper condition for rapid and complete combustion. The theoretical amount of air needed to completely burn one pound of gasoline is 15 pounds. Since ideal conditions do not exist in an engine, from 16 to 18 pounds of air must be supplied for each pound of fuel for complete combustion. Such a ratio of air to fuel will not give maximum power however because then the engine is pumping through a large amount of air which is not combining with the fuel to produce heat and work. From 12 to 12.5 pounds of air per pound of fuel are necessary for maximum power.

¹ For the measurement of airplane engine power in flight see the National Advisory Committee for Aeronautics Bulletin No. 252, 1927.

With this mixture ratio, enough fuel is supplied to insure that all the oxygen of the air is being used in combustion.

Elements of a simple carburetor. — A diagrammatic sketch of a simple carburetor is shown in Fig. 121. The air enters through a *venturi nozzle* shown at 8. The flow of air is regulated by a *butterfly throttle valve* 1. The fuel enters the carburetor from the fuel tank through the pipe 12. Its flow is regulated by the *needle valve* 4. The chamber into which the fuel is admitted is called the *float bowl*. It is open to the atmosphere at the top and contains the *float* 3 which actuates the needle valve by means of the rollers 5 and levers pivoted at 6. When the fuel level is low the float sinks, the rollers are lowered and the needle valve rises admitting more fuel. Jet 11, which is fed by reservoir 9 and the tube 10 from the

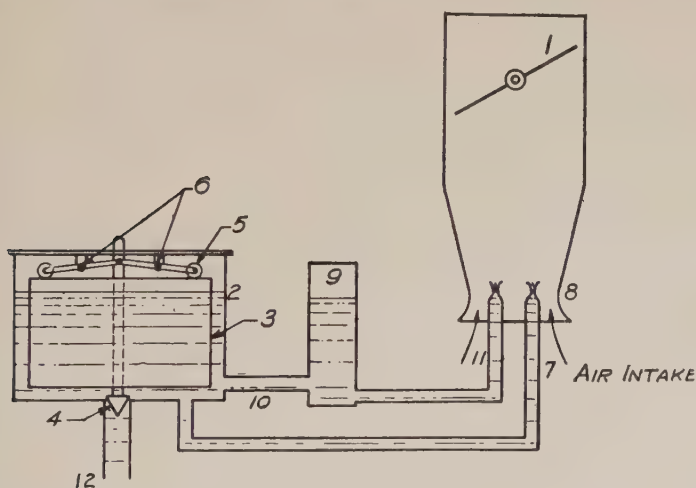


FIG. 121. Elements of a simple carburetor. Float bowl 2 and accelerating well 9 are open to the atmosphere.

float bowl, is a *compensating* and *accelerating jet*, the action of which will be explained in the next paragraph.

Operation of a simple carburetor. — The carburetor operates as follows: A piston descending on its suction stroke creates a vacuum

in the intake manifold above the throttle valve. With the throttle valve open air will be drawn up through the venturi throat. The vacuum will cause the fuel to overflow the main and compensating jets. The air, which travels at a high velocity through the venturi throat, picks up the drops of fuel from the jet tips and carries them by the butterfly valve, into the cylinder. The law governing the flow of air through the venturi throat and the flow of the liquid fuel from the jet are not the same. The result is an over-rich mixture supplied to the engine at high engine speeds and a lean mix at low engine speeds unless some compensating device is added to the carburetor. A simple compensating device which involves no moving parts is shown in Fig. 121. A small orifice causes the fuel to run slowly from the tube **10** into the reservoir **9**. Before the engine is started the level of fuel in the reservoir will be the same as in the float bowl. Upon starting the engine, fuel will be supplied to the engine from both jets. When the engine gains speed, fuel will be taken from jet **11** faster than it can be supplied to the reservoir by the tube **10**. The fuel level in the reservoir will fall until the fuel goes directly from tube **10** out jet **11**. Since tube **10** cannot supply enough fuel to fill jet **11** there will be a mixture of air and fuel supplied by this jet at high speeds. The extra air entering through jet **11** compensates for the excess of fuel that is supplied by jet **7** at high speeds. Hence the name compensating jet.

When the throttle valve is closed, as when the engine is running at part load, there is a high vacuum in the riser pipe above the throttle valve. Because of the low pressure, the fuel, which has been deposited on the riser pipe walls, evaporates, cooling the walls. When the throttle valve is opened up quickly, as in accelerating the engine, the fuel and air mixture entering the riser is chilled. As a result some of the fuel condenses and deposits on the riser walls. **The result is a very lean mix entering the cylinders with liability of back-firing through the carburetor.** The compensating jet aids in eliminating this trouble in the following manner. With the engine running at part load and low speed, little fuel is taken from jet **11**. The reservoir fills up nearly to the float bowl level. When the

throttle valve is opened suddenly, jet 11 supplies only liquid fuel for several revolutions, thus making up for the fuel which deposits on the riser walls.

Thus it is seen that the compensating jet tends to make a leaner mix at high speeds by supplying auxiliary air and little fuel. It tends to make a richer mix at low speeds by supplying all fuel and no air. It supplies an excess of fuel for a few revolutions when accelerating, to replace that deposited on the cold riser walls.

Atomization in the carburetor. — At any given velocity, air can carry small drops of liquid better than it can carry large drops. Furthermore, the smaller the fuel drops, the larger will be the surface exposed to the oxygen in the air and the more rapid and complete will be the combustion of the fuel in the cylinder. It is therefore very important that the fuel be very finely atomized ¹ in the carburetor.

Atomization in the carburetor is attained, in part, by the breaking up of the fuel drops by the air-stream as the drops are torn from the fuel jets. This is usually not enough atomization to give good distribution and combustion. A common means of obtaining further atomization and some vaporization of the fuel is by use of a "hot spot" around the throttle valve.

The "hot spot" is produced by by-passing some of the exhaust gas around the part of the riser pipe in which the throttle valve is located. As the fuel is thrown against the sides of the riser pipe in passing the throttle valve it is further broken up by impact, whether a "hot spot" is used or not. Without the "hot spot" some of the fuel may remain on the riser around the throttle valve. With the "hot spot" the fuel skitters off and is further broken up much as a drop of water skitters and is broken up on a hot stove.

After the fuel has been finely atomized so the air-stream can carry it by the throttle valve, there is the problem of distributing the air and fuel to the cylinders without causing the fuel to drop out of the air-stream in some part of the intake manifold. This will

¹ See National Advisory Committee for Aeronautics Technical Memo. No. 518, June, 1929.

be discussed in the next paragraph. The preceding paragraphs on the carburetor treat of a simple carburetor only. The carburetor for an airplane engine is much more complex. It must function in all positions. It must not be affected by change of altitude or low temperatures. The fundamental ideas of carburetion are not changed however. The carburetor must function as described in the preceding paragraphs regardless of the above conditions. A more complicated design is necessary to make this possible.

Fuel distribution. — Fuel distribution is accomplished by the intake manifold. Its purpose is to take the charge with the same proportions of air to fuel as delivered by the carburetor and to distribute equal portions to each cylinder. To accomplish this best, the resistance to air flow from the carburetor to each cylinder should be approximately equal. It is inevitable that some fuel should deposit on the manifold walls. Therefore, the manifold should be designed to get this fuel back in the air-stream, so that slugs of liquid fuel will not be supplied to any of the cylinders. The easiest way to accomplish this is to make all the bends in the manifold piping 90 degree bends with sharp corners, as is done in many automobiles. This allows the fuel to be torn from the edges by the air in passing. It does not, as formerly thought, increase the resistance to air flow and decrease the power of the engine to any appreciable extent.

The ability of air to carry fuel increases rapidly as the air velocity goes up. It is evident that decreasing the size of the riser and intake manifold pipes will cause a higher air velocity and better carrying power. These pipes should be made as small as is possible without affecting the power output of the engine. In automobile engines the air velocity through the riser pipe is roughly three times the car speed.

The flow of air through the intake manifold is not continuous and in a single direction. When an intake valve closes, the flow in the portion of the manifold leading to it stops. In the main pipe of the manifold there will still be flow in the direction of the

intake ports which are still open. A moment's consideration will show that the flow is very interrupted even at high speeds. At low speeds, because of the late closing of the intake valve, some of the charge which has entered a cylinder may be forced back into the intake manifold to cause a reversed flow in the manifold. This is known as "**blow-back.**" It results in a loss of power, because of decreased charge in the cylinder, and also in poor distribution, because of the fuel that falls from the air-stream when the flow is reversed.

Detonation. — Under certain conditions of operation some engines are heard to give forth a sharp metallic sound. When they do this they are said to detonate. Detonation was once referred to, (and by some still is referred to), as "carbon knock" or as "pre-ignition." It was thought that red-hot carbon in the engine caused pre-ignition of the charge with an abnormal pressure rise which caused the sound to be heard. The carbon knock explanation had to be discarded when it was found that perfectly clean engines could be made to detonate. Some still insisted that pre-ignition occurred causing the sound. However, engines made to pre-ignite purposely made no knocking noise. Neither were abnormally high pressures reached during the operation. This seemed to indicate that the detonation was an explosion occurring during the operation rather than relatively slow burning such as would be caused by pre-ignition.

Many theories have been presented as the explanation of the explosion in the cylinders. The true cause of detonation is not known at present. Investigations carried on in England revealed that during the early stages of combustion of all detonating fuels, such as ordinary gasoline and kerosene, certain peroxides were formed. It was also discovered that no such peroxides were formed during the early stages of combustion of fuels such as benzenes and alcohols which were known not to detonate. It is well known that many peroxides are very highly explosive. It is therefore thought probable that peroxides are formed during the early stages of combustion until their quantity is so great as to cause an

explosion which travels through the combustion chamber at or above the speed of sound, causing the knock so commonly heard.

Even though the cause of detonation is not exactly known, many of the factors controlling detonation are known. Detonation is affected by the kind of fuel used, as mentioned above, by the combustion chamber shape, the location of the spark plug, and the location of the valves.

The more volatile the fuel, the less is the detonation. Various compounds have been discovered a small amount of which will prevent the less volatile fuels from detonating. The most common of these compounds is tetra-ethyl lead, used in ethyl gasolines.

The effect of the combustion chamber shape on detonation will be discussed in the following paragraph.

Types of combustion chambers. — The four requirements for a good combustion chamber are: first, it should be shaped to give and maintain maximum turbulence of the entering charge; second, there should be no obstruction to the entry of the gases which would reduce the amount or velocity of charge taken in; third, there should be no pockets in which a quantity of stagnant gas might lie; and fourth, the spark plug should be located centrally.

Turbulence produces good mixing of the new and old charge in the cylinder, thus preventing the occupation of any one part of the cylinder by gas so dilute that it is not combustible. This is important at light loads when the amount of new charge is small. Then, the burnt gases, being the same amount as at full load, are a greater proportion of the total charge. Turbulence also tends to spread the flame mechanically throughout the combustion chamber. This reduces the time necessary to complete the combustion and therefore reduces the time for formation of peroxides and the tendency to detonate.

With the spark plug placed centrally the time of combustion is a minimum, since the distance for flame travel is equal in all directions. Therefore the time for the formation of the peroxides (assuming this explanation for the cause of detonation as true) is a minimum, reducing the chances of detonation.

Several types of combustion chambers are shown in Fig. 122. From the requirements for the ideal combustion chamber it would

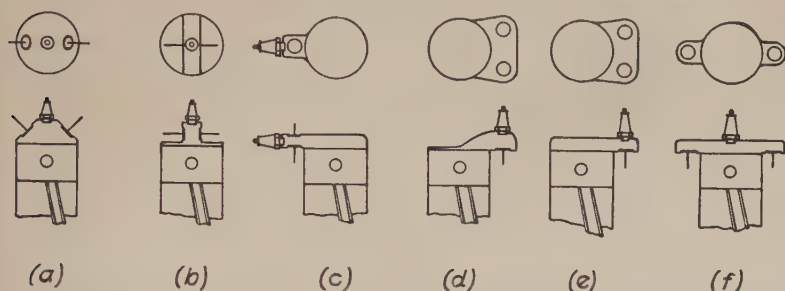


FIG. 122. Types of cylinder heads showing valve and spark plug arrangement. Top views of (d), (e) and (f) are with cylinder head removed.

seem that a hemispherical combustion chamber with the spark plug placed at its center would be very nearly ideal. This shape is mechanically difficult and locating the spark plug at the center is impossible.

The *penthouse* type combustion chamber shown at (a) Fig. 122 is the closest practical approach to the ideal combustion chamber. It is not good from the mechanical standpoint because it necessitates valves set at an angle and two cam-shafts instead of one. It is very good thermodynamically and is used on sleeve-valve engines. The spark plug, while not located at the geometric center of the chamber, is located in such a position that the flame travel in all directions is equal. This type of chamber with two spark plugs placed horizontally and on opposite sides of the chamber, was in the Wright Whirlwind engines used by Colonel Charles Lindbergh, Clarence Chamberlin, and Commander Richard Byrd on their separate trans-Atlantic flights made in 1927.

The chamber shown at (d) Fig. 122 is called the *Ricardo* head for its inventor Harry R. Ricardo. It is very good from the standpoint of turbulence and detonation. The shape of the chamber when the combustion starts approximates that of the ideal combustion chamber.

The form of combustion chamber shown at (c) Fig. 122 produces turbulence but because of the long flame travel it is very bad with

regard to detonation. It can only be used with low compression ratios.

The form of combustion chamber shown at (b) Fig. 122 is very good both with respect to detonation and turbulence. Because of the change in direction of the entering charge this type of chamber suffers a loss of power at high piston speeds because of the reduction of charge entering the chamber.

The type of chamber shown at (e) Fig. 122 is the one most commonly used in automobile engines. It may be used as shown or with overhead valves and the spark plug in the side of the wall. This type is very poor with respect to both turbulence and detonation. It is called the *L*-head.

The type of chamber shown at (f) Fig. 122 is the worse possible from turbulence and detonation standpoints. It permits close cylinders and simplified manifolding but it is thermodynamically poor. It has the longest flame travel of any shown. This type is known as the *T*-head.

Effect of altitude and supercharging. — Because of the decrease in the density of the air at high altitudes the engine will not take in the same weight of charge per cycle as at sea level, and will therefore not deliver as much power as at sea level. In order to obtain as much power from the engine at high altitudes as at sea level some device must be used to furnish air to the intake manifold at sea level density. A high speed turbo-blower or supercharger is the most common means of supplying air at increased densities. The supercharger may be driven by an exhaust turbine, a separate engine, or by the main engine. The high speed of the supercharger, 12,000 to 30,000 R.P.M., makes gearing necessary if it is to be driven by an engine. This makes added weight. If driven by an exhaust turbine the back pressure of the engine is raised, thus reducing its output slightly.

Because of decreased air density at high altitudes the ordinary radiation surface is not sufficient to cool the engine. If water-cooled, a larger radiator and more cooling water must be used. This means more weight and resistance.

As long as the supercharger is capable of delivering air to the engine at sea level density, the engine will deliver the same power as at sea level. Unless the pilot is equipped with oxygen apparatus, the maximum altitude attainable is limited by his ability to withstand the abnormal conditions of the upper atmosphere rather than by the performance of the engine, since superchargers can be made to deliver air at sea level density when operating in an atmosphere where respiration is impossible.

Equations are available for the calculation of the output of engines² without superchargers at any altitude, from their sea level output and the density of the air at the altitude at which the engine is to operate.

Valves and valve arrangement. — The function of the valves is to permit the admission of fresh charge to the cylinder and the escape of burnt charge from the cylinder at predetermined intervals with the least expenditure of energy possible. The valves should offer the least possible obstruction to flow. Since heating of the entering charge reduces the weight of charge taken in per cycle and heating of the exhaust valve causes it to oxidize and warp, it is important that these valves be able to dissipate heat rapidly. Therefore it is better to use valves with a small diameter and volume and a large lift than to use large valves and a small lift. The smaller valves have a larger heat dissipating area per unit volume than do the larger valves.

Several valve arrangements are shown diagrammatically in Fig. 122. The valve arrangement and combustion chamber shape are interdependent, the fixing of one determining the other. The arrangement shown at (a) is much used in airplane engines where excellent performance is of more importance than expense.

Valve operation and valve gear. — The opening and closing of the intake valve determines the amount of charge that is taken into the cylinder each cycle. Its opening and closing is controlled by a *cam* carried on a *cam-shaft*. Since, for a four-stroke cycle en-

² See National Advisory Committee for Aeronautics Bulletin No. 225.

gine, the intake valve opens once in every two revolutions, the cam-shaft must be geared to run at one-half crank-shaft speed.

The exhaust valve must be open for a sufficient length of time to insure the expelling of most of the burnt charge. The gases passing over it are very hot. The exhaust valves on heavy duty engines running at full load often operate at red heat. The exhaust valves may or may not be driven from the same cam-shaft as the intake valves, depending on the valve arrangement.

One arrangement of valves and valve gear is shown in Fig. 123. The valves are encased in the castings seen on the top of each cylinder. They are operated by means of long *tappet rods* running inside the tubes which are visible running from the crank case to the tops of the cylinders. These tappet rods push on one end of a *rocker arm* which is pivoted at the middle. The other end of the



FIG. 123. Curtiss Challenger six cylinder, air-cooled engine.
Front view.

rocker arm is in contact with the valve stem. When the cam pushes the tappet rod and the one end of the rocker arm up, the other end of the rocker arm goes down opening the valve port.

The valves are returned to their closed positions by springs. The valves are accessible through openings in the castings in which they are enclosed. These openings are covered by plates which are visible in Fig. 123.

Ignition systems. — There are two main types of ignition systems used for gasoline engines. In one a high tension magneto is used to produce the ignition spark and in the other a high tension coil and battery are used. An aircraft engine may use either of the two systems. Some are equipped for both systems for greater reliability and safety.

The high potential produced by the magneto or high tension coil is impressed across the points of a spark plug. A spark jumps

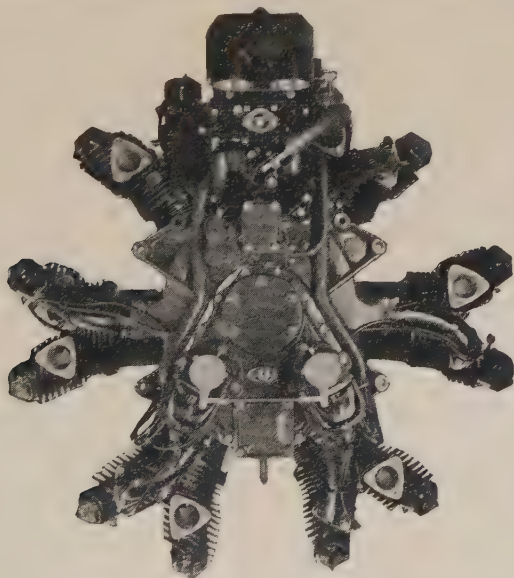


FIG. 124. Curtiss Challenger six cylinder, air-cooled engine. Rear view, showing grouping of accessories.

across these points igniting the fuel. The intensity of the spark has been found to be of importance only when the cylinder contains a weak or lean mixture of air and fuel. For light duty and

low compression engines the spark plug should have long thin points with low heat dissipating capacity. This permits the points to run at a high enough temperature to keep the oil burned from them and thus prevents oil fouling. For heavy duty and high compression engines, the cylinder temperature is usually high enough to rid the spark plug points of oil without special design. Then it is best to use thick short points with good means of dissipating heat, as such points are much more durable than the thin ones. The location of magnetos and spark plugs on a radial engine are shown in Figs. 124 and 128.

Spark advance. — As mentioned previously, spark advance is necessary to insure completion of combustion by the time the exhaust valve opens. The amount of spark advance necessary depends upon the speed at which the engine is run and upon the mix ratio. The spark advance necessary to give maximum power at any given load, speed, and mix ratio is called the optimum spark advance for those running conditions. It has been found that the optimum spark advance is such that three-fourths of the total combustion takes place before the piston reaches head-end dead-center. As mentioned in the paragraph on the real Otto cycle indicator card, this causes one-half the pressure rise to occur before head-end dead-center is reached and the other half after this position is reached.

Since spark advance is necessary because of the time required for combustion, anything that will speed up the combustion will reduce the amount of spark advance necessary. Several things affect the time of combustion or flame speed. The flame speed increases as the charge is made richer, up to a certain point. It increases with increase in compression ratio, intake temperature, and increased turbulence. An increase in engine speed causes an increase in intake velocity and turbulence. The flame speed decreases as the new charge is diluted by burnt gas at part loads.

It is evident then that an increase in compression ratio, intake temperature, ratio of fuel to air, engine speed, or load will cause a decrease in the optimum spark advance.

Engine speed. — In the chapter on the power available from the propeller it was shown that the propeller efficiency was a maximum at a speed between 1200 and 2000 R.P.M. The power available from an internal combustion engine increases up to a certain point with engine speed. The speed for normal operation of the engine may be anywhere from 1200 to 3000 R.P.M. If it is desired to power the airplane with an engine whose normal or rated speed is over 2000 R.P.M., it must be connected to the propeller by a set of reducing gears which will reduce the speed of the propeller to its speed of best efficiency with the engine running at rated speed. An engine of this type is shown in Fig. 125. If the rated engine speed falls in the range of best propeller efficiency the propeller can be directly connected to the engine crank-shaft thereby saving the weight and expense of the reducing gears.

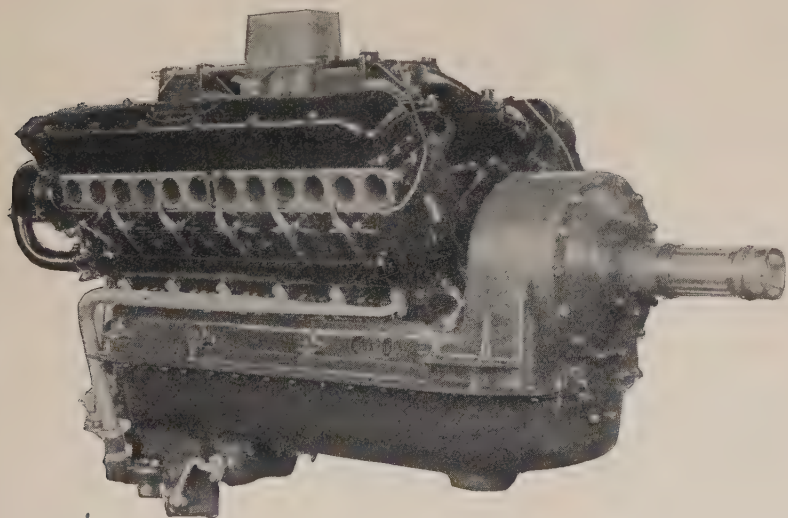


FIG. 125. A Curtiss Conqueror V-type, water-cooled engine. Propeller shaft is connected to the crankshaft by reducing gears.

Cooling systems. — There are two cooling systems in common use for aircraft engines. These are the air-cooling systems and the water-cooling systems.

To provide cooling by air the engine cylinders are made with projecting fins to give as much radiating and air contact surface as possible. Figs. 123, 124, 127 and 128 show such engines.

To provide cooling by water the engine cylinders are surrounded by chambers known as water-jackets through which water is circulated. The water, in turn, is then pumped through radiators where it delivers the heat abstracted from the engine cylinders to the air. Figs. 125 and 126 show a water-cooled engine.

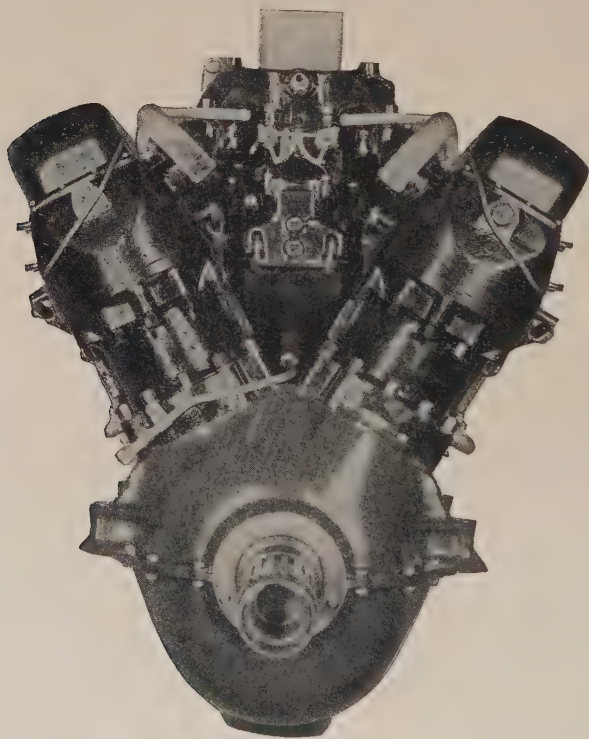


FIG. 126. Curtiss Conqueror V-type, water-cooled engine. Front end view showing location of accessories. This engine not geared.

It is apparent that if the air can be circulated around the cylinders in such a manner that each cylinder can be cooled as effectively as by water cooling, the elimination of the radiators, cooling water,

pipng, and water pump should give a substantial reduction in weight of the complete power plant. This is the aim of the exponents of the air-cooled engines.

The air-cooled engines in common use are practically all of the radial type shown by Figs. 123, 124, 127, and 128. An air-cooled engine with the cylinders in line, like the ordinary automotive engine, is being developed in an effort to reduce the large parasite drag which is caused by the large frontal area of the radial engines. This drag can also be greatly reduced by the use of proper cowling.



FIG. 127. Wright Whirlwind J-6, nine cylinder, air-cooled engine with cooling to reduce parasite drag. This engine is rated at 300 H.P. at 2000 R.P.M.

A new method of cooling engines has been developed by the Army Air Corps at Wright Field, Dayton, Ohio. It involves the use of ethylene glycol (known commercially as Prestone) for the cooling agent instead of water. This liquid is a polyhydric alcohol which is clear, colorless, odorless, and has a boiling point of 387 degrees Fahrenheit. Because of its high boiling point the engine

can be run at a temperature of around 300 degrees Fahrenheit instead of 180 degrees as with water-cooling. The greater temperature difference between the radiator and air allows the dissipation of the same amount of heat from a much smaller radiating area. The result is that for a certain engine and plane only four and one-

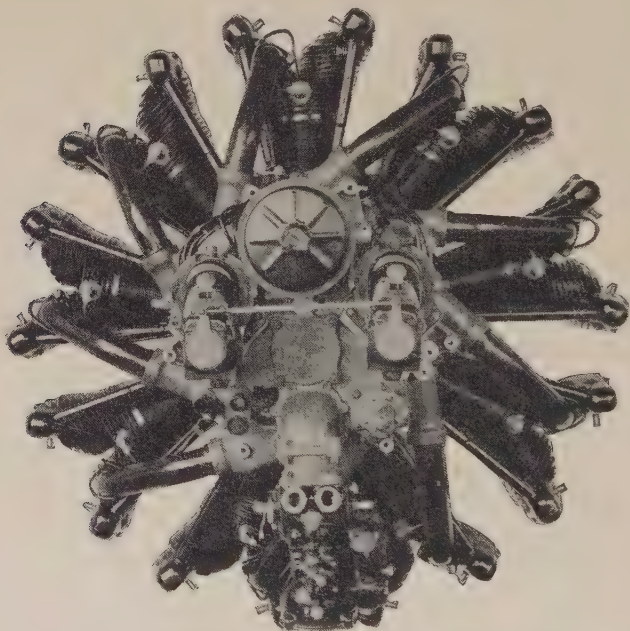


FIG. 128. Wright Whirlwind nine cylinder, air-cooled engine. Rear view, showing grouping of accessories on rear section of crank case.

half gallons of ethylene glycol are needed in place of about eighteen gallons of water. This is a reduction of about eighty-four pounds in weight of cooling fluid.

The decrease in the amount of cooling liquid allows a reduction of about seventy-five per cent. in radiator size. The reduction in radiator size greatly reduces the parasitic drag and weight of the radiator.

Very slight changes are said to be necessary to change from water-cooling to cooling by this chemical. The engineers of the

Army Air Corps report that the increase in the running temperature of the engines tested showed no injurious effects.

The reduction in weight and drag with this method of cooling improve the climbing qualities, maneuverability, fuel and oil consumption, and speed of the airplane. The increase in speed has, in at least one case, been from fifteen to eighteen miles an hour over the planes with the original radiator designed for water-cooling. The mechanical efficiency is increased because the higher running temperature reduces the viscosity of the oil and the friction loss.

The results of various experiments utilizing the latent heat of vaporization of water or some other liquid for cooling engines, indicate that efficient cooling can be obtained with much less cooling liquid and radiator area than if water-cooling is used, because of the high latent heat of vaporization as compared with the specific heat of water. For example, for a temperature rise of 20° F., one pound of water would carry off 20 B.t.u. of heat, whereas one pound of steam formed with the same temperature rise would carry off 990 B.t.u. This results in a substantial reduction in the weight and drag of the cooling apparatus. In addition it is possible to use the steam from evaporative cooling for heating the interior of a cabin plane with small increase in weight and no addition to the drag. It seems probable that further development of steam or evaporative cooling systems will be made in the future.

Lubrication. — Proper lubrication is very essential in aircraft engines which must run at nearly full power for hours at a time. Three types of lubricating systems may be used. These types are splash feed systems, systems in which oil is supplied in small measured quantities to each bearing, and forced feed systems.

In the splash feed systems oil is fed continuously into troughs into which the ends of the connecting-rods dip. A very small amount of oil is forced into the bearings with the result that although lubrication may be fairly good, not enough oil is forced through the bearings to provide any cooling by the oil. This method is considered satisfactory only for very light bearing loads and is therefore very rarely used for the bearings in aircraft engines. It

is often used for cylinder lubrication, however. The oil consumption, with this type of lubrication, is very high because of the large amount of oil splashing about on the cylinder walls working up into the combustion chamber.

With the system in which a measured quantity of oil is fed to each bearing, a large number of pumps are necessary because each cylinder must have its independent lubrication. Because the oil is fed directly to the bearings, the oil consumption is much less than with the splash system. However, since the amount of oil fed to each bearing is just the amount needed for lubrication alone, this system provides no cooling of the bearings by the oil.

Where both lubrication and cooling of the bearings by the oil is desired, a pressure lubrication system is used. Its purpose is to circulate as much oil through the bearings as possible and to keep the oil as cool as possible. It should be understood that the oil pressure is not high enough to cause the load to be fluid borne because of that pressure. The pressure is merely high enough to insure circulation of the proper amount of oil through the bearings. The oil pressure necessary increases with decrease in bearing clearance and with increase in viscosity of the oil. As the engine heats up and the viscosity of the oil drops, the oil pressure will be seen to drop, as less pressure is then required to force the same amount of oil through the bearings. For proper lubrication and cooling the pump should be capable of delivering about one-half gallon of oil per brake horse power of the engine per hour.

To insure that the oil gets into the bearings, even with pressure feed systems, the oil holes must be located in the region of least pressure of the bearing. This region will probably not be the same for the connecting-rod and main bearings. It must be determined by a step by step analysis of the gas and inertia forces acting throughout a cycle.

Because the pressure lubrication system is good for very heavy bearing loads, it is used almost exclusively in aircraft engines. The oil is pumped through holes drilled in the crank-shaft to outlet holes in the bearings.

Many aircraft engines have what is called a dry sump. This

means that the portion of the crank case in which the oil collects as it falls from the bearings, is drained by a pump so that it is kept nearly dry at all times. The oil is pumped to a storage tank, separate from the engine, from which it is again circulated. This method of disposing of the oil is necessary since the engine would not be capable of running in all positions if the sump were full of oil. It also simplifies the problem of cooling the oil because it can be pumped through a radiator and then to the storage tank if additional cooling of the oil is desired.

Weight and compactness. — In aircraft engines weight and compactness are of prime importance. Reduction in weight and size of the engine for the same power output increases the weight and space that may be taken up by useful load. Because of the necessity for light weight, cast iron cannot be used for many of the parts for which it is normally used in automotive engines. The cylinders are almost always made of steel with a light steel water-jacket for water-cooled engines. The cylinder head is often made of cast steel but may be made of aluminum. Duralumin forgings have been used for crank cases. The forgings are more sound and of lighter section than castings would be. The pistons may be made of aluminum or cast steel. The connecting-rods may be of steel or of duralumin.

By carefully choosing the material to be used for each part the weights of aircraft engines have been steadily decreasing as shown by the tabulation in Chapter VI.

Compactness of the unit makes for greater pay loads and less head resistance. The use of ethylene glycol for cooling purposes promises substantial reductions in both size and weight.

An analysis of one modern air-cooled engine shows the total weight of the engine to be comprised of various materials in the following proportions:

Aluminum alloys.....	42.0 %
Steel	54.2 %
Copper, brass, and bronze.....	3.6 %
Rubber, paper, etc.....	0.2 %

Arrangement of cylinders. — The cylinders of the aircraft engine may be arranged in a variety of manners. Although air-cooled in-line engines are likely to come into common use, air-cooled engines are, at present, almost always of the radial type with several cylinders arranged radially around a single crank as shown in Fig. 129 (a). Engines of this type are shown in Figs. 123, 124, 127 and 128.

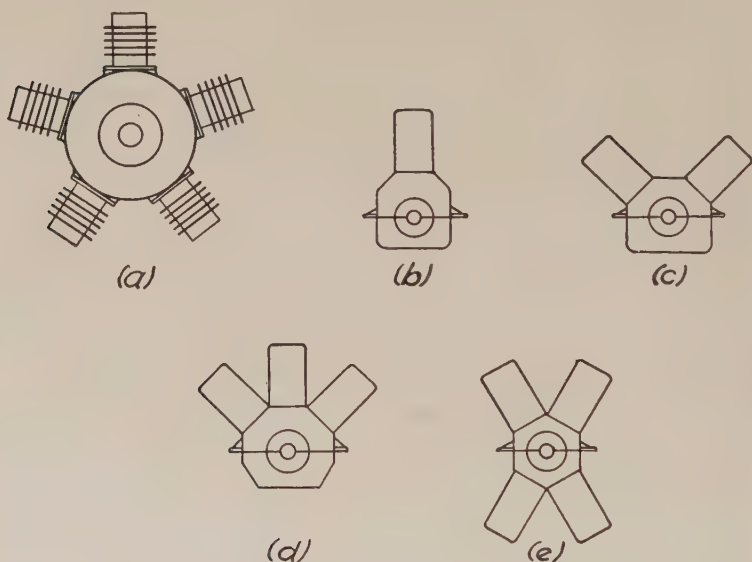


FIG. 129. Arrangement of cylinders in aircraft engines.

Water-cooled engines may have their cylinders arranged in several different ways. At (b) Fig. 129 is the common type of engine with several cylinders in a single line. At (c) Fig. 129 is the arrangement known as the V-type engine in which the cylinders are arranged in two rows instead of one. An engine of this type is shown in Figs. 125 and 126. When the cylinders are arranged in three rows instead of two, as shown at (d) Fig. 129, the engine is known as a W-type engine. Engines with four rows of cylinders in the form of an X are called X-type engines. The arrangement

of cylinders for this type is shown at (e) Fig. 129. An engine of this type is shown in Fig. 130. The W-, V-, and X-type arrangements are used to reduce weight, to make the engine

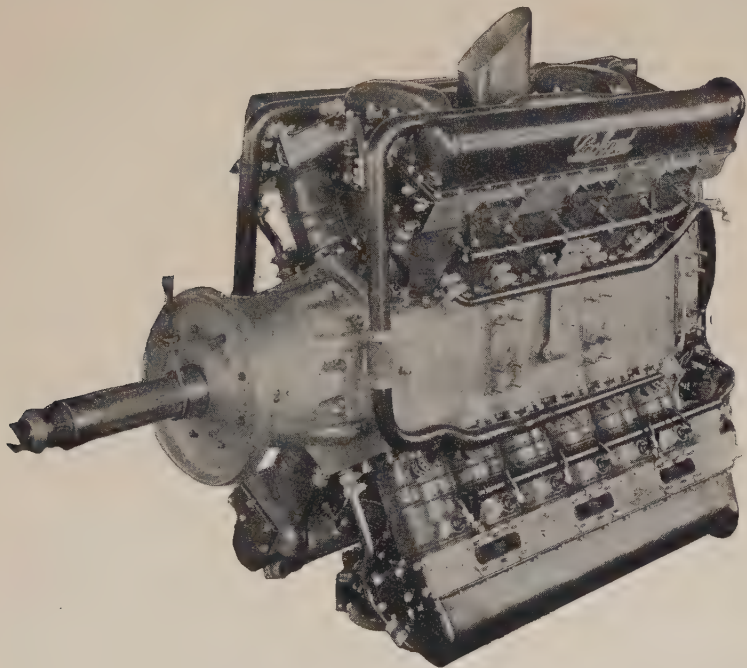


FIG. 130. A three-quarter view of the Packard, 24 cylinder, X-type airplane engine.

compact, and to eliminate vibrations. With any of these types more than one piston is operated by a single crank thus reducing the length of crank-shaft and crank case necessary. Because of opposing inertia forces of the pistons and connecting-rods of the different banks of cylinders much of the vibration is eliminated.

Diesel engines for airplanes. — At the present time practically all airplane engines use gasoline for fuel. However, the Packard Motor Car Company is developing an engine to operate on fuel oil with low volatility. This is a 9-cylinder, radial, air-cooled

engine capable of delivering 225 horse power at 1950 R.P.M. It operates on a four-stroke cycle. The cycle differs from the original Diesel cycle in that the fuel is directed into the cylinder at a high pressure but without the use of injection air. The cycle is also practically a constant volume cycle instead of a constant pressure cycle.

This engine uses a single valve for admission of air and for exhausting the burnt gases. It is illustrated diagrammatically in Fig. 131. The engine is also shown mounted on the airplane in which it was tested in Fig. 132. The use of a single valve and cooling by air are the radical departures from modern Diesel engine practice. It is thought that these two innovations are, in part, responsible for the low weight of less than 3 pounds per horse power.

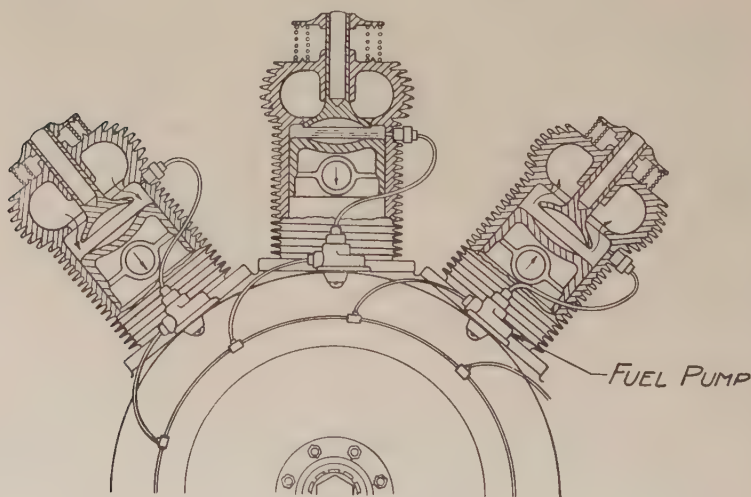


FIG. 131. Diagrammatic representation of Packard single-valve Diesel aircraft engine.

Because no carburetion is necessary, the intake piping has been omitted. The exhaust pipe can be omitted also, thus saving in weight.

A master connecting-rod and eight articulated connecting-rods

are used in this engine as in other radial engines. Fuel is fed to the spray valve, mounted in the side of the cylinder, by means of a cam-operated fuel injection pump. Each cylinder has a separate pump so that failure of one pump would disable only one cylinder.

The cycle is performed as follows. In Fig. 131 the cylinder at the left is on the suction stroke, the air entering the cylinder through the port controlled by the single valve. When the piston

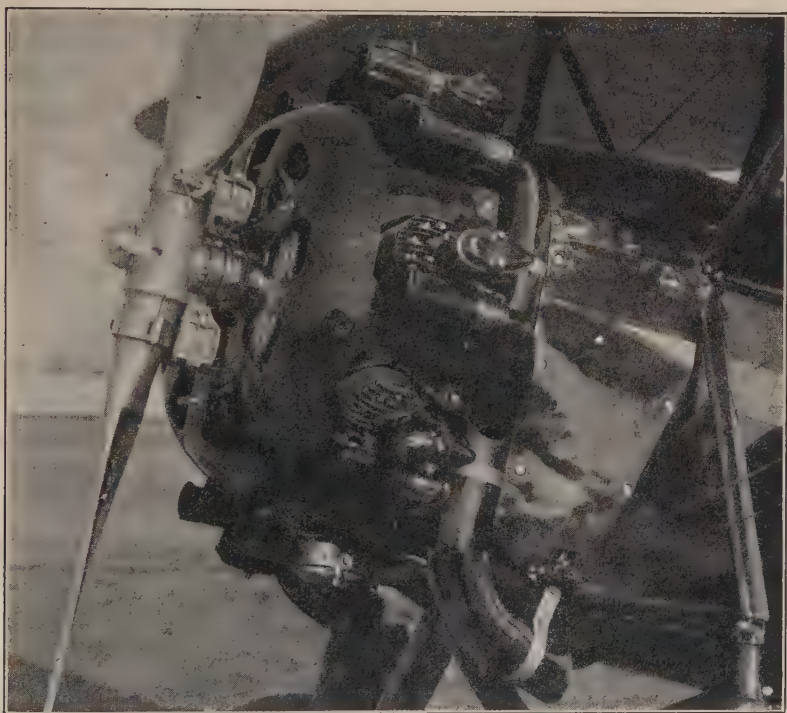


FIG. 132. A view of the Packard Diesel engine, showing the mounting and the cowling used. Note the shock absorbing device between the propeller and the cowling.

has completed its suction stroke the valve closes and the air is compressed in the cylinder. At some period of the compression stroke the cam-operated fuel injection pump forces fuel in through the fuel spray, as shown by the center cylinder. The heat of com-

bustion causes expansion of the gases. This forces the piston back on the power stroke. The fuel is not sprayed into the cylinder during much of the power stroke. At the end of the power stroke the valve opens and the burnt gases are forced out of the cylinder by the returning piston, as shown by the cylinder at the right. This completes the cycle of operation.

Differences between gasoline, low speed Diesel, and high speed Diesel engines.³—Typical indicator cards from the different types of engines will be used to bring out their differences, see Fig. 133.

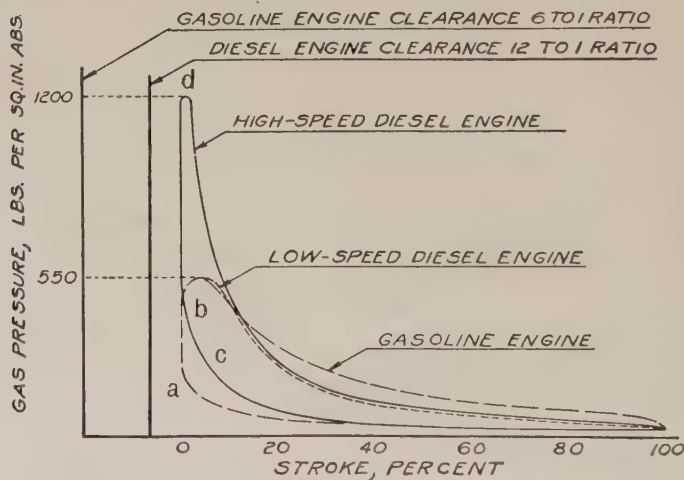


FIG. 133. Typical indicator cards for gasoline, low speed Diesel, and high speed Diesel engines.

With the gasoline engine compression is carried to some such point as *a* on the indicator card. Ignition occurs and the pressure rises abruptly to the peak pressure of about 550 pounds per square inch. Because of the abrupt pressure rise this cycle is called the constant volume cycle.

³ See paper by L. M. Woolson, "Diesel Engines for Aircraft," Society of Automotive Engineering Journal, February 1929.

With the low speed Diesel engine, the compression is carried to point **b**. Fuel is injected at this time and the combustion occurs at such a slow rate that the pressure does not rise much above compression pressure. That is, the burning takes place as the piston is going away from the gas. This cycle is known as the constant pressure cycle.

In the high speed Diesel engine the beginning of fuel admission occurs before **b** at some such position as **c** so that ignition and combustion occur while the piston is traveling toward the gases, decreasing their volume. Nearly all of the combustion is completed when the piston reaches head-end dead-center. The result is a very high pressure, as shown at **d**.

The long narrow card of the high speed Diesel engine gives an indicated mean effective pressure of about 120 pounds per square inch as against 150 pounds per square inch for the gasoline engine.

Low weight of Packard Diesel engine.⁴ — The low weight per horse power of the Packard Diesel engine has been achieved by simplification and unique design. The engine needs neither carburetor, magneto nor intake manifold. The elimination of these parts represents a substantial reduction in complication and weight. By using a single valve for intake and exhaust, one-half of the customary valve operating mechanism is also eliminated. Besides the reduction in weight effected by the monovalve construction, better valve operation is obtained, since the alternate exhaust of hot gases and intake of cold air through the same port keeps the valve cooler and prevents its warping and wearing.

The crank case is especially designed to obtain lightness. It is a light aluminum casting, made in one piece to avoid heavy flanges and bolts. Instead of using many studs to fasten the cylinders to the crank case, the cylinders are provided with grooved lugs which project parallel to the crank-shaft axis. Two circular hoops of alloy steel encircle the cylinder lugs in contact with the crank case,

⁴ See paper presented by L. M. Woolson at Detroit Aeronautic Meeting of the Society of Automotive Engineers in April, 1930, entitled "The Packard Diesel Aircraft-Engine."

one at the front and one at the rear of the engine. These hoops are tightened by means of turnbuckles, until the stress in the hoops is greater than the stress resulting from the explosions in the cylinders under load. This puts the crank case under a high initial compressive load. When in operation, the load caused by the cylinder pressures increases the tension in the hoops, causing them to expand slightly, thus reducing the compressive load on the crank case, but at no time transferring any tension load to it. This construction permits the use of a casting weighing only 34 pounds for the crank case.

The crank-shaft is made light by having the counterweights pivoted on the crank-shaft and cushioned between heavy compression springs, instead of being rigidly connected to the crank-shaft. The propeller is, likewise, cushioned between rubber blocks carried on the extremities of two arms fastened to the crank-shaft. Thus, when the crank-shaft is suddenly accelerated by the very high peak pressures in the cylinders, there is a lag before the counterweights and the propeller are again driven solidly by the crank-shaft. This allows the peak pressure, which is of very short duration, to be expended before the solid driving occurs and in this manner greatly reduces the shock loading of the crank-shaft. The propeller shock absorber can be seen in Fig. 132. This cushioning allows the use of a crank-shaft comparable to that of a gasoline engine of equal rating.

Means by which high speed is attained. — The ordinary so-called high speed Diesel engine has a maximum speed of about 1200 R.P.M., whereas the Packard Diesel is rated at 1950 R.P.M. Most all Diesel engines of the ordinary type are equipped with a multiple pump unit located somewhat remotely from the cylinder heads in which the spray nozzles are located. The enormous pressures, necessary for high speed operation, cause pressure surges in the tubing connecting the pumps to the nozzles. This results in incorrect fuel injection timing. Often air is trapped in the tubing causing misfiring.

In the Packard Diesel engine, each cylinder is equipped with its own self-contained fuel-pump and nozzle unit, thus eliminating the

necessity of the tubing carrying the high pressure. This insures correct injection timing and eliminates trouble from air pockets. The fuel-pump and nozzle units and their operating rods are shown on the rear of the cylinders in Fig. 134.

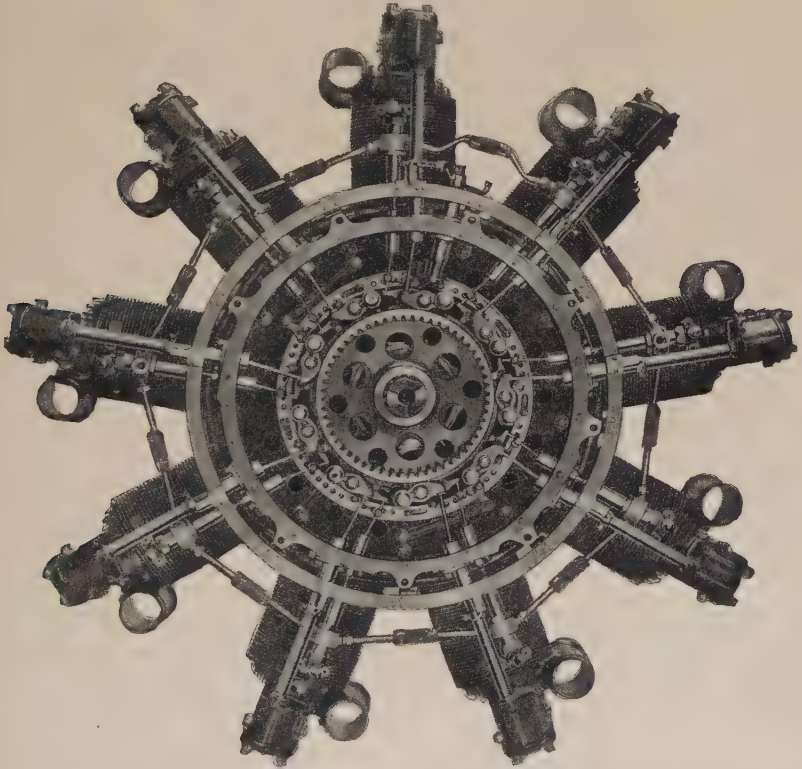


FIG. 134. Rear view of the Packard Diesel engine with rear cover plate removed, showing the cam ring which operates the valves and fuel pumps. Note the stream-lined cases enclosing the rocker arms.

Increased turbulence in the cylinders means better mixing of fuel and air and insures faster and more complete combustion. To get turbulence in the Packard engine the intake port is shaped like a flattened venturi and is arranged tangentially to the bore of the cylinder, thus imparting to the entering air a rapid whirling motion. The turbulence is further increased by an eccentrically located

pocket in the piston head. By the means explained in the preceding paragraphs, sufficiently accurate injection timing and turbulence are obtained so that the rated speed of 1950 R.P.M., and over, can be had with this new engine.

Speed control is effected by the pilot by means of the regular throttle control lever, which, instead of being connected to the butterfly valve of an intake manifold, is connected to a device which changes the length of stroke of the fuel-pumps. Thus the pilot can regulate the amount of fuel injected per revolution per cylinder and consequently the speed of the engine.

Starting and stopping the engine. — The conventional inertia type starter is used for cranking this engine. The throttle is held wide open during cranking, admitting a maximum of fuel for starting. In ordinary weather the engine starts immediately on its regular fuel supply. For starting in extremely cold weather, the engine is equipped with *glow plugs*, these being merely incandescent heating elements for igniting the fuel at starting when the compression temperature is too low to ignite it. The glow plugs are necessary only at extremely low temperatures but their presence is not detrimental to the ordinary operation of the engine.

To stop the engine, it is only necessary to completely close the throttle. This shortens the stroke of the fuel-pump until the pump plunger barely moves. This shuts off the fuel supply and the engine stops.

Advantages of the Diesel engine over the gasoline engine. — The advantages claimed for the Diesel aircraft engine over the gasoline aircraft engine are:

- (1) The Diesel engine is inherently far more reliable than the gasoline engine because the electric ignition system is eliminated and a separate fuel injection system is applied to each cylinder, thus assuring maximum dependability.
- (2) The fire hazard is reduced because of the use of low volatile fuel.

- (3) The fuel consumption per horse-power-hour output is reduced about 20 per cent.
- (4) The fuel cost per horse-power-hour is reduced about 70 per cent.
- (5) Engine operation is not affected by temperature and humidity ⁵ conditions.
- (6) Radio interference is eliminated by the omission of the electric ignition system.
- (7) Basic reliability of the Diesel engine justifies a reduction in the number of power plants in large transport planes and presages a consequent important reduction in the cost of maintenance and operation of commercial air transportation lines.

⁵ Gasoline engines have their power reduced by increased humidity. See National Advisory Committee for Aeronautics Technical Memorandum No. 309, June 1929.

CHAPTER XV

THE CONSTRUCTION AND EQUIPMENT OF THE FAMOUS "SPIRIT OF ST. LOUIS"

A general discussion of airplane construction is beyond the scope of this volume. Airplane construction will be found to vary with each type of airplane and with each manufacturer. In the present chapter the discussion will be limited to an explanation of the construction and preparation of Colonel Lindbergh's New York-Paris airplane, the "Spirit of St. Louis,"¹ which is noteworthy, in this connection, not only because of its famous performance, but also because it is reasonably typical of airplane construction, and because it serves as an example of how an airplane must be designed for its particular purpose.

Basic specifications. — The basic specifications for this airplane were determined by Colonel Lindbergh himself. They were as follows: The airplane should be a monoplane type, powered with a single Wright J-5-C engine. It should have a good power reserve on take-off when carrying more than 400 gallons of gasoline and must have the pilot's cockpit located in the rear of all fuel and oil tanks, for safety in a forced landing.

It was thought, before these specifications were received, that the standard Ryan M-2 airplane could be so modified as to be satisfactory for the proposed flight. Upon receipt of the specifications it was decided that it would be easier to redesign than to modify the standard type craft.

Fuselage. — The standard design was followed as closely as possible for the fuselage. Because of the heavy fuel load the plane

¹ The material and photographs for this chapter were obtained from the National Advisory Committee for Aeronautics Technical Note No. 257, by Donald A. Hall, Chief Engineer, Ryan Airlines, Inc.

was to carry, the fuselage members had to be strengthened. The frame-work for the fuselage is shown in Fig. 135. The frame-work was constructed of metal tubing with welded joints. This gave a very strong, light, and rigid construction.

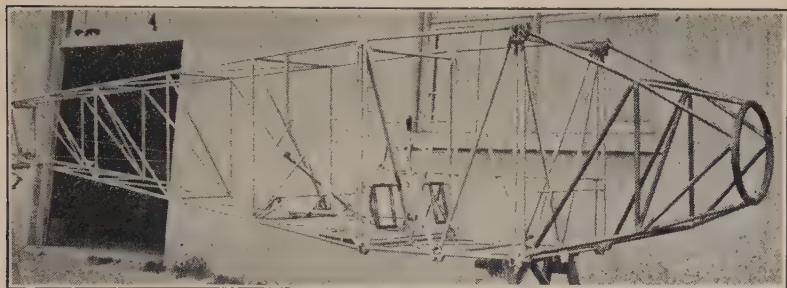


FIG. 135. Fuselage frame-work for the "Spirit of St. Louis."

Wings. — To support the heavy load the wing span was increased to 46 feet, 10 feet greater than the span of the standard Ryan M-2 airplane. The wings had a 7-foot chord. The wing-area was 319 square feet. The structural members of the wing cellule



FIG. 136. Wing construction of the "Spirit of St. Louis."

were redesigned to give greater strength than those of the standard plane. The wing rib spacing was reduced to 11 inches. The wing used is shown in Fig. 136.

Because of their increased moment arm, with the increased wing span, the ailerons were reduced in area. They were located in, somewhat, from the wing tips as shown in Fig. 136. This was expected to decrease the deflection of the wing tips and to increase the aerodynamic efficiency of the wings. The airfoil section was the Clark Y type.

Landing gear. — Because of the increased wing span and for increased safety, the landing gear had an exceptionally wide tread. The axles were made of chrome molybdenum steel tubing. This was heat treated to give a tensile strength of 180,000 pounds per square inch.

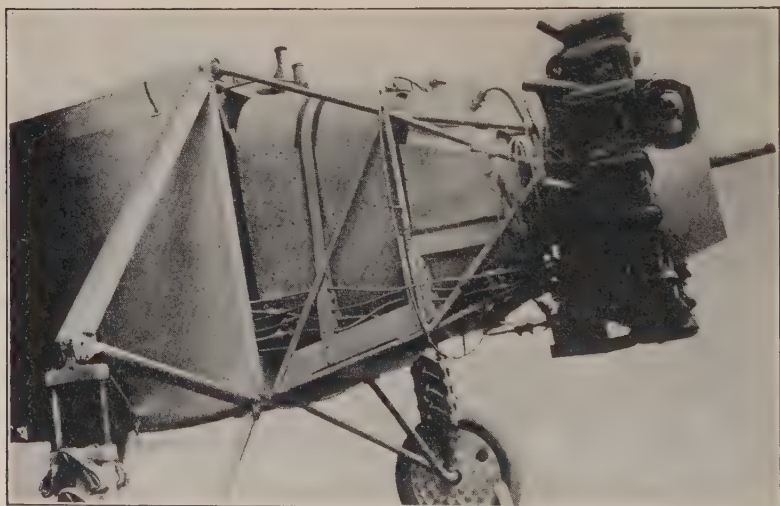


FIG. 137. Landing gear and trombone type shock absorbers used on the "Spirit of St. Louis." Note, also, location of gas and oil tanks.

The shock absorbers used were of the trombone type with 8 individual links of cord and a $6\frac{1}{2}$ inch rise. Fig. 137 shows the landing gear and shock absorbers before the shock absorber cover-

ings were in place and before the landing gear was stream-lined. Fig. 138 shows the completed landing gear.

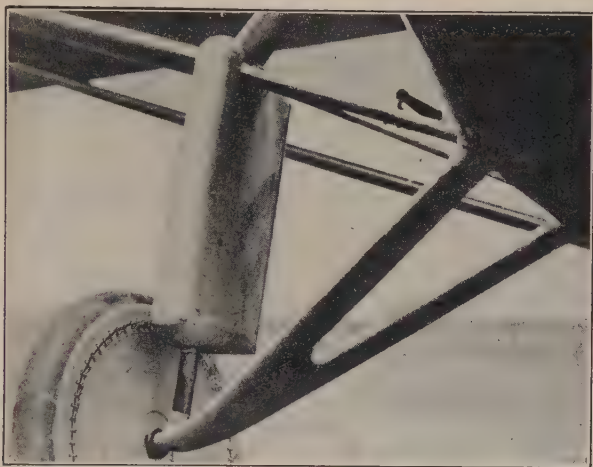


FIG. 138. Completed landing gear used on the "Spirit of St. Louis."

Tail surfaces. — The tail surfaces used on the "Spirit of St. Louis" were practically the same as those of the standard M-2 plane. They were installed 2 feet farther aft because of the lengthened fuselage. The tail surfaces are well shown in Fig. 139. The tail

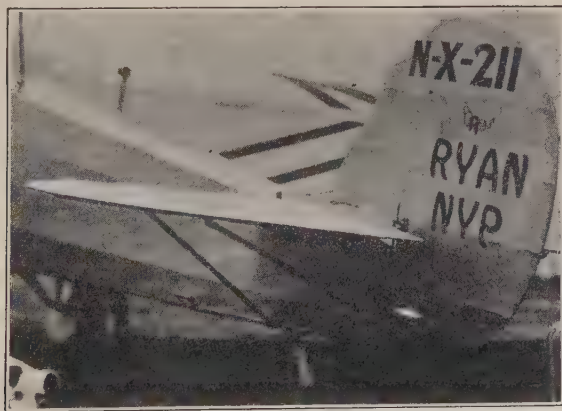


FIG. 139. Tail surfaces of the "Spirit of St. Louis."

skid was made of heat-treated chrome molybdenum steel tubing of the same quality as the axles.

Pilot's cockpit. — The location and design of the pilot's cockpit were the most radical features of the whole design. It was located in the rear of the fuselage as shown by the location of the control levers in Fig. 135 and by the location of the windows in Fig. 140.



FIG. 140. A side view of the completed "Spirit of St. Louis."

The cockpit was so located to obtain the greatest possible safety. It was entirely enclosed and permitted vision only from the side and upper windows, as shown by Fig. 141. For frontal vision a retractable periscope was used. An angular mirror about 3 inches by 5 inches mounted on the upper left of the instrument board, as shown in Fig. 141, allowed the pilot to see what was in front. The instruments used in flight are shown in this same picture.

Fuel and oil tanks. — There were five separate fuel tanks. Three of these tanks were in the wings. The remaining two were between the cockpit and the engine as shown in Fig. 137. The combined capacity of the three wing tanks was 152 gallons. The large center fuselage tank had a capacity of 210 gallons and the smaller forward tank a capacity of 88 gallons. The total fuel capacity was 450 gallons.

All the gasoline tanks were connected to a Lunkenheimer dis-



FIG. 141. Interior view of the cockpit of the "Spirit of St. Louis."

tributer in the cockpit making it possible to pump fuel from any tank to any other tank. The engine was provided with two fuel systems. An econometer invented by Colonel Lindbergh was used on the fuel systems to indicate fuel flow.

The front tank shown in Fig. 137 was the 25-gallon oil tank. It was so located to act as a fire wall between the engine and pilot.

Power plant. — The power plant for the "Spirit of St. Louis" was a single Wright J-5-C, 9 cylinder, radial, air-cooled engine, capable of delivering 223 B.H.P. at 1800 R.P.M. A regular stock model was used. The thrust was obtained from a dural propeller made by the Standard Steel Propeller Co. It was set at $16\frac{1}{4}$ ft. pitch. The engine was located farther forward than customary to provide proper balance. The oil tank mentioned above was fitted into the extra space thus obtained.

Stream-lining. — The stream-lining used on the fuselage was entirely new. It was worked out so that any longitudinal section

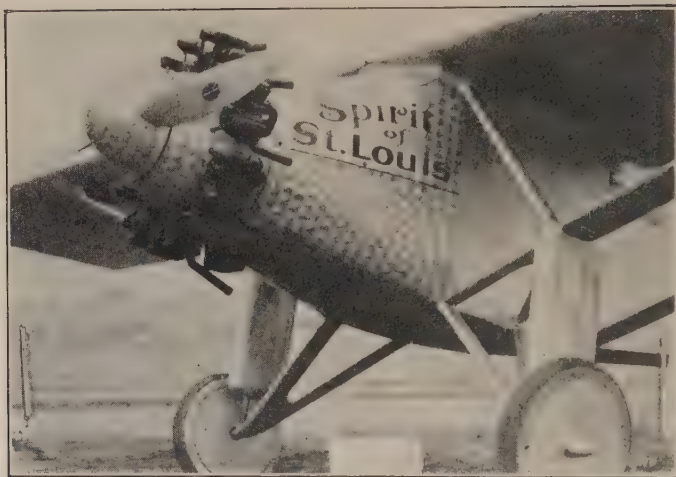


FIG. 142. Quarter view of engine and propeller used on the "Spirit of St. Louis."

of the fuselage gave a smooth curve from propeller spinner to tail. The junction of the bottom of the wing and the fuselage was filleted and stream-lined. All exposed parts such as landing gear parts, wing braces, and tail skid were stream-lined to reduce parasite drag.

Weight. — The weight of the empty plane with full equipment of instruments but not including fuel, oil, the pilot or other miscellaneous items was 2150 pounds. The load of about 450 gallons of fuel added 2750 pounds. The oil, 20 gallons at about 7 pounds per gallon, made 140 pounds more. The pilot and the miscellaneous articles taken by him weighed about 210 pounds giving a total weight of 5250 pounds. At the end of a flight which would consume all the fuel and 15 gallons of oil the weight would be 2415 pounds.

Loading. — With full load at the start of the flight the wing loading was 16.50 lbs. per sq. ft. The power loading at the start of the flight was 23.6lbs. per B.H.P. figuring on 223 B.H.P. at 1800 R.P.M.

Testing the plane.² — The tests made on the airplane were all planned by Colonel Lindbergh himself. In all of the test flights Colonel Lindbergh was the pilot. In fact he is the only pilot who has ever flown the "Spirit of St. Louis." Enough tests were made on the airplane to insure that the theoretical calculations for performance were correct.

² For a comparison of the test results with theoretical calculations see National Advisory Committee for Aeronautics Technical Note No. 257, July 1927.

CHAPTER XVI

SPECIAL TYPES OF HEAVIER-THAN-AIR CRAFT

The previous chapters have dealt with the airplane as a land craft with stationary wings, which obtained its lift entirely by reason of the upward force acting on the wings when moved at high speed through the air. This chapter will be devoted to explaining how the airplane is modified to make it capable of landing on water and to explaining some types of aircraft which are not designed along conventional lines.



FIG. 143. A Vought "Corsair" seaplane being prepared for use in the United States Navy.

Seaplanes. — A seaplane is an airplane designed to rise from and alight on the water. Pontoons take the place of the landing wheels of the land plane. This type of machine is invaluable in the naval service as it permits scouting in places where there are bodies of water but no landing fields. A seaplane is shown in Fig. 143. It will be noted that the lower wings of this type of seaplane have

pontoons attached. This aids in keeping the machine upright in case a poor landing or rough waters cause a wing to dip to one side.

Very high speeds have been obtained with seaplanes. Just after the Schneider Cup Races of 1929, A. H. Orlebar of Great Britain flew a Supermarine Rolls-Royce seaplane at the average speed of 357.7 miles per hour for four laps of the three kilometer course. In a previous flight he completed one lap of the course at a speed of 368 miles per hour, *a speed of over six miles per minute*. The wings of this plane had very sharp leading edges, the designers sacrificing lift for high speed.

Some of the cruisers of the United States Navy are equipped

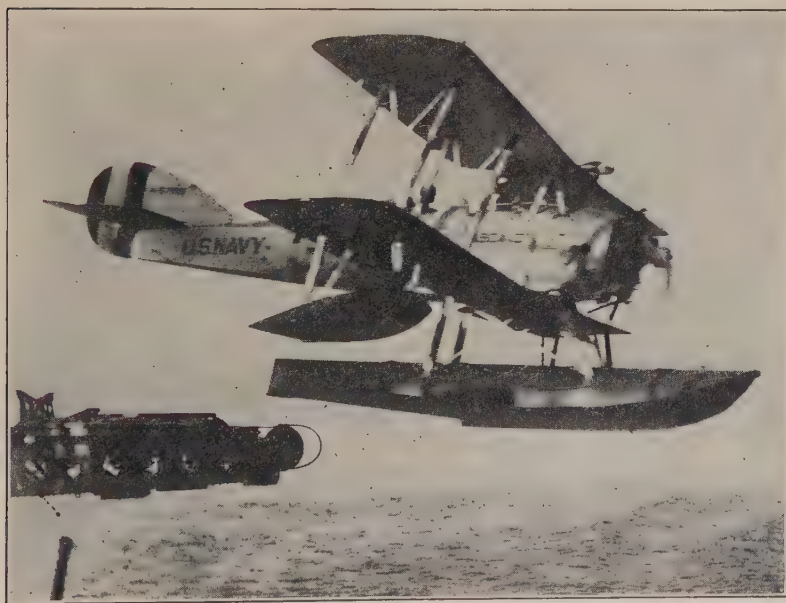


FIG. 144. A Vought Navy seaplane whizzed off to a flying start from a catapult on the deck of the U. S. S. Cincinnati while in Chinese waters.

with catapults for launching seaplanes. Fig. 144 shows a seaplane being launched by means of a catapult. On returning to the ship, the seaplane lands in the water and is hoisted to the ship deck by means of a crane. The United States Navy also has two airplane

carriers, the Lexington and the Saratoga. These ships have long runways built on them thus enabling land planes to take-off and land from these runways. The runways are equipped with arrangements for bringing the ships to rest quickly to prevent over-running the runways.

Flying boats. — A *flying boat* differs from a seaplane in that the pilot's quarters, instead of being in a fuselage above the pontoons used for floating the machine, are in a boat-like hull which rests in the water when the machine is at rest. This hull (usually a single hull) serves as a pontoon for floating the craft on the water as well as for the pilot's and passengers' accommodations. A flying boat is

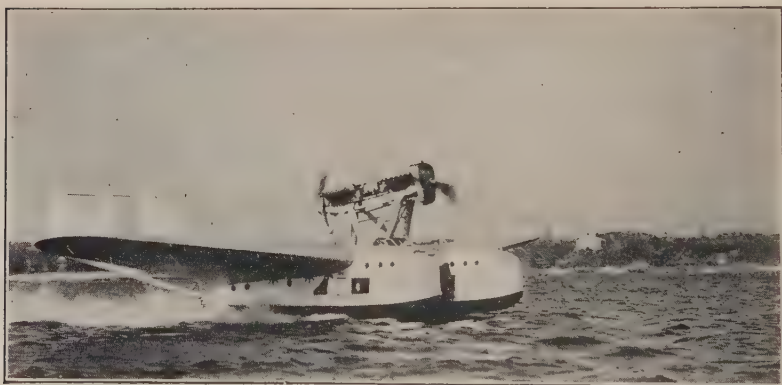


FIG. 145. A large S-55 Savoia-Machetti flying boat. The machine has two propellers, one pusher and one tractor. It carries 14 passengers.

shown in Fig. 145. It is to be noted that this plane has two cabins or hulls for housing the pilots and passengers, this construction, however, being unusual. It also has two engines and propellers, a pusher and a tractor. By having the propellers rotate in opposite directions the effect of propeller torque on lateral stability can be eliminated.

The world's largest airplane is the Dornier DOX flying boat, a machine of German construction. It has a capacity of 100 passengers and operating crew. The machine has a wing-span of 157

feet. It has a length of 149 feet. The machine is powered by means of twelve engines and twelve four-bladed propellers. The total power output of the engines is 6000 horse power. These power units are located on top of the upper wing and are arranged in six pairs in tandem, similar to those shown in Fig. 145.

Utility of seaplanes and flying boats. — For many purposes seaplanes or flying boats are superior to land planes. As mentioned before, they can be used for exploring new territory which has waterways but no land suitable for landing. For flights over bodies of water so large that an airplane could not glide to shore if motor trouble developed, a machine of either of these two types is by far the most desirable. A practical illustration of their value is the instance of the Savoia-Machetti flying boat acting as escort to Lady Heath in her flight across the Mediterranean. This flying boat, with a crew of three, developed motor trouble in the middle of the Mediterranean and was forced to land. It floated for four days in heavy seas before it was found. This ship was perfectly seaworthy and had experienced no serious strain. A land plane would have sunk almost immediately with the probable death of its crew.

For coast-wise, lake or river travel the seaplane or flying boat is ideal. No special landing fields need be provided. The whole body of water acts as a landing field. Their utility is well illustrated by comparing the times required to make a Washington to New York flight by land plane and by seaplane or flying boat. By land plane the time required for the flight would be about an hour and a half. The journeys to and from the airports at the end of the trips consume another hour and a half making a total of three hours by land plane. The time required by seaplane would be the flight time, an hour and a half, plus a few minutes at each end of the trip in getting from the water to the destination. If landing lanes were provided in the harbors the total time consumed by seaplane would probably be two hours at the most. By rail the trip takes from four to five hours. Many persons, now traveling by rail, would undoubtedly travel by air if the time could be reduced from four

or five hours to two. The saving of a single hour or so on the trip by traveling by land plane is not usually considered worth while.

Furthermore, it is not an impossibility to land a seaplane or flying boat on land without serious damage. This has been demonstrated by several pilots who forgot to lower their retractable wheels when landing an amphibian on the ground. Thus, it is not as dangerous to fly a seaplane inland as it is to fly a land plane over large bodies of water.

Amphibians. — A flying boat or a seaplane fitted with wheels, so that it can operate from both land and water, is called an *amphibian*. A machine of the former type is shown in Fig. 146 and one of the latter type is shown in Fig. 147. Amphibians are doubly useful in being able to operate from both land and water. The wheels are often retractable, thus reducing the parasite drag. They are folded up or retracted when operated in the water to cut down the water resistance.

Helicopters. — A machine which is capable of rising vertically by reason of support derived from the vertical component of thrust produced by rotating airfoils is called a *helicopter*. To date there have been no successful helicopters. A successful helicopter would be invaluable to aeronautics. It would permit landing and taking off from very restricted areas. As before mentioned, aviation is handicapped by the relatively large distances at which most of the airports are located from the business districts of the large cities. This necessitates further automobile, street car, or train travel to reach the business districts after landing at the airports. A successful helicopter would allow landings in the business districts, thus eliminating the tiresome trip to and from outlying airports.

The helicopter would also permit landings in small clearings in forested areas or on comparatively rough surfaces such as might be encountered in polar explorations. At present many places of interest must be viewed from the air alone because of the impossi-



FIG. 146. An S-56 Savoia-Machetti amphibian.

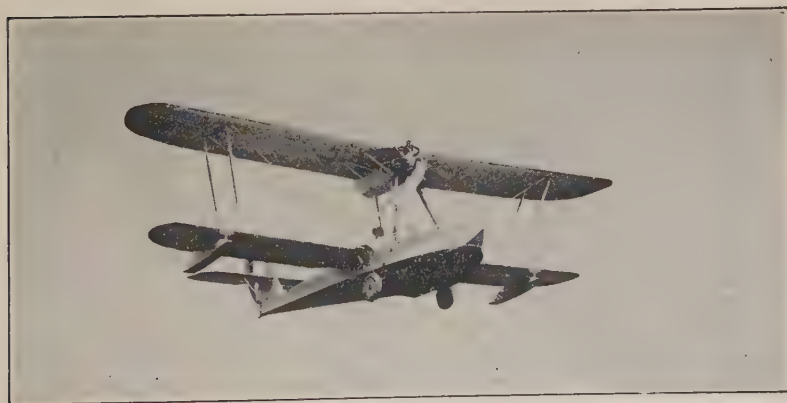


FIG. 147. A Vought "Corsair" amphibian.

bility of making safe landings. The autogiro, described in the next paragraph, is a machine which permits of shorter runs after landing.

The Autogiro. — The *autogiro* is an airplane which in general appearance resembles the low wing monoplanes. The outstanding difference is a horizontal rotor with four 15-foot blades which is mounted on a vertical shaft over the forward cockpit of the machine. The wings are abbreviated, being only 25 feet long, most of the lift being obtained from the horizontal rotor. This rotor is not power driven, but is caused to rotate by the action of the air on the blades as the machine moves forward. The vanes of the



FIG. 148. The "Autogiro."

rotor do not move in a horizontal circle but rise and fall as they rotate. This machine is shown in Fig. 148. Forward motion is obtained by means of the engine and propeller mounted on the nose of the machine.

The autogiro is not a helicopter. It is an airplane so modified as to greatly reduce the landing speed, and run after landing. It is

said that landing speeds of 20 miles an hour with runs of only 7 to 10 feet after landing have been accomplished. Against a wind equal to the landing speed, the machine will land vertically. The cruising speed of the machine is about 85 miles per hour with a top speed of about 105 miles per hour. The stability of the machine is much greater than that of an ordinary airplane because of the elevated position of the center of lift. It is like the parasol monoplane in this respect. It is said that the machine will maintain altitude at the very low speed of 25 miles per hour. When the speed is reduced below this, it shows no spinning tendencies but simply enters its normal gliding angle of about 6.5 to 1. It is said to be able to climb at the rate of about 500 feet per minute. The autogiro needs a slightly longer run than the ordinary airplane for take-off. If the take-off run could be reduced, the machine would be ideal for short trips to and from the city, such as transporting passengers to and from the outside airports to air-line terminals located centrally in the city. If a sufficiently short run was attained, runways might be constructed on building tops in the cities.

The "Helicogyre." — A machine called the "*helicogyre*," invented by an Italian engineer named Signor V. Isaaco, is being built by the British Air Forces for experimental purposes. It has a horizontal rotor as does the autogiro. This rotor is not caused to rotate by air forced on its vanes as in the autogiro. It is driven by motors mounted either in the middle or at the ends of the rotor vanes or wings. The entire sustentation of the machine is obtained from this rotor, the small stationary wings of the autogiro being omitted. This machine is shown diagrammatically in Fig. 149.

The small vane engines have their own gasoline tanks located in the vanes. The vanes of the rotor have ailerons attached. Increased lift is obtained from the rotor by lowering these ailerons with consequent change of the attack angle and camber of the vanes. In a lecture before the Royal Aeronautical Society in London, it was stated that 30 pounds per horse power could be lifted with a rotor consisting of four vanes of improved design.

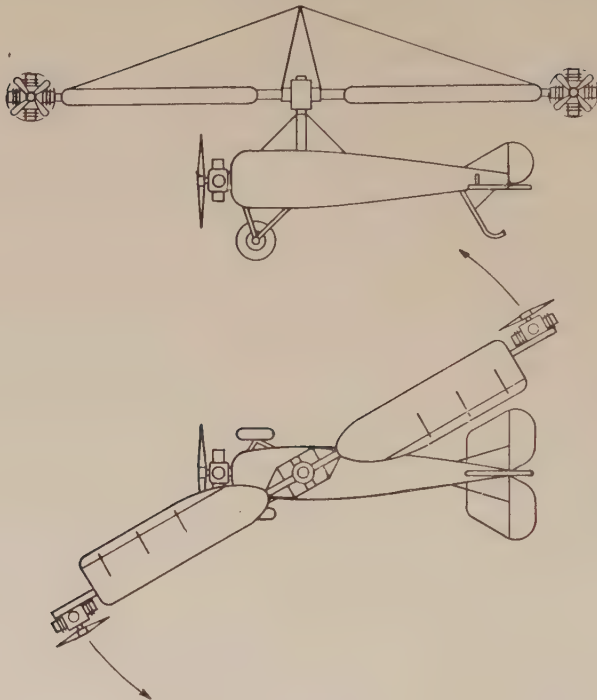


FIG. 149. Diagrammatic arrangement of the "Helicogyre."
Side and top views.

If the vane engines of this machine fail for any reason, it is said that, by means of the engine and propeller in the nose of the machine, it will continue in flight as an autogiro. Several flights have been made with this type of craft in England.

The Merrill type airplane. — The *Merrill type airplane* shown in Fig. 150 was conceived and planned by A. Merrill of the California Institute of Technology. The wings on this machine are not fastened rigidly to the fuselage, but are fastened together by struts pivoted at each end. The upper wing is attached to the fuselage by a pivot fastened to the rear spar, and the lower wing is attached to the fuselage indirectly through the struts and upper wing and also by the control levers.

The wings can be made to take any position within the limits indicated in Fig. 150 while in flight, the position and angle of

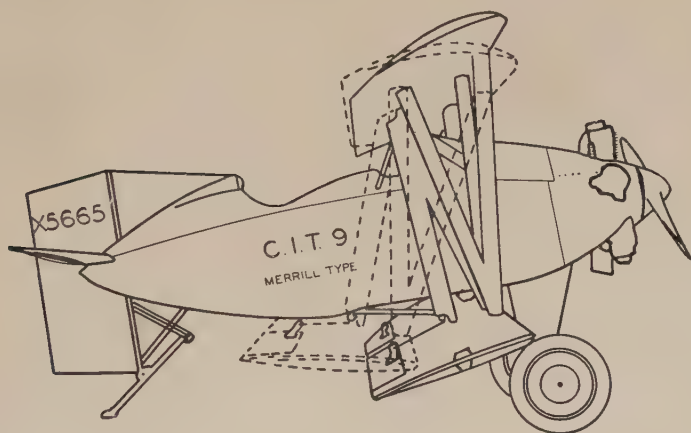


FIG. 150. The Merrill type airplane with movable wings. The two extreme positions of the wings are indicated.

attack of the wings being controlled by a crank at the pilot's side. Since the wings are movable, the fuselage remains in a horizontal position whether ascending, descending or flying horizontally. Shifting the wings allows the center of lift to be changed with respect to the center of gravity while in flight. In this manner the pitching moment of the plane can be controlled without recourse to the tail surfaces. The stabilizer of the ordinary airplane is omitted on the Merrill plane. Movement of the wings replaces the elevator action.

When the pilot wishes to ascend or descend he sets the wings at the required angle and he will continue to ascend or descend until he returns the wings to a horizontal position. During this time the pilot has only to control the plane with respect to direction and rolling, the pitching taking care of itself. This type of airplane is said to be entirely free from the danger of spins when stalled. While the distance required for taking off is as long as with an ordinary machine, this type of airplane is said to come to a

stop in about 40 feet after it touches the ground. It has a high gliding angle, permitting landing in restricted areas.

The Curtiss Tanager. — The airplane called the "Tanager," made by the Curtiss Aeroplane and Motor Company, was the winner of the Daniel Guggenheim Safe Aircraft Competition prize awarded in February, 1930. This airplane, shown in Fig. 150a, has three important characteristics which enabled it to win this prize.

First, the Tanager cannot be accidentally put into a spin. Expert pilots tried, unsuccessfully, all known methods of putting the plane into a spin. Therefore it seems safe to say that it cannot be spun accidentally and probably cannot be spun purposely.



FIG. 150a. The Curtiss "Tanager" showing slots, flaps and floating ailerons.

Second, the necessity for accurate judgement of heights has been eliminated in flying this plane, thus making it safe for one having defective depth perception to pilot it. The Tanager has been stalled repeatedly at varying heights up to 200 feet. When so

stalled, the plane settles down to the ground in landing attitude without picking up speed. The shock of such a landing is no more than that from landing in an ordinary plane, because of the long stroke oleo shock absorbers with which the Tanager is equipped.

Third, the control operation is greatly simplified. With this plane, movement of the ailerons causes rolling without yaw, thus making use of the rudder, to keep direction, unnecessary. This is due to the use of a new type floating aileron and a slotted flap on the trailing edge of the wing. The machine can be flown into and out of all normal flying positions, including tight vertical banks, without use of the rudder. To turn right or left the pilot merely steers to right or left as in an automobile and the machine banks itself properly and turns in the direction required. Pushing forward on the control causes the plane to nose down and pulling back causes it to nose up.

The Tanager is built around the Curtiss "Challenger" engine, a 176 h.p. engine of the radial air-cooled type. The wing-sections are of the Curtiss 72 outline. The wings are equipped with automatic slots on the leading edges; a slotted flap on the trailing edges and the *floating ailerons*, previously mentioned, carried on the lower wings.

The automatic slots in the leading edges of the wings start to open at an angle of attack of 12° and are completely open at 16° . With the slots closed, the angle of attack for maximum lift is at 16° ; with the slots open the maximum lift is obtained at a 26° angle of attack. The increase in lift obtainable by using the slots and the flaps is apparent from the following table of maximum lift coefficients:

Condition of the wing	K_L
Basic Curtiss 72 wing-section	0.0033
With rear slot open	0.0035
With rear slot open and flap down	0.0044
With front slot open also	0.00605

The Curtiss floating ailerons are symmetrical airfoil sections,

aerodynamically balanced by having the pivot back of the leading edge, and statically balanced by addition of weight to the leading edge. These ailerons float freely in the air-stream at all times, the pilot having no control over this action. He is able to displace the ailerons with respect to each other but not with respect to the fuselage or wings. A movement of the stick corresponding to an angle between the ailerons of 8° , causes one aileron to float up 4° from the relative wind and the other to float 4° down from the relative wind. Since the aileron sections are symmetrical and identical and have the same angle with the relative wind, the drag on both ailerons will be the same. Thus rolling is obtained without yaw.

The absence of spinning, the ability to land safely from stalled positions due to the slot and flap construction, and the simplification of control operation due to the floating ailerons, make the Curtiss Tanager the safest and the most easily operated plane constructed to date.

Ornithopters. — For many years man has attempted to learn the secret of flight by studying birds. It was partly due to this study that the airplane was developed. However, the principles of airplane flight and the principles of bird flight, while similar, are not identical. An airplane cannot rise vertically, nor can it hover in still air as a bird can. The earliest attempts at flying machines were machines having wings that could be flapped like those of a bird and were called *ornithopters*. As yet, none have been successful. It seems unlikely that the ornithopter will be a success because of the many mechanical difficulties encountered in such a design.

Bellanca Tandem airplane. — The Bellanca Tandem airplane, popularly known as the "*Flying Gas-tank*," was designed by Giuseppe Bellanca. The first model, shown in Fig. 151, was designed primarily for a gasoline carrier for long flights. The airplane has a total gasoline capacity of 2200 gallons, this being carried in four separate tanks. The main fuselage tank holds 1500 gallons, the largest single airplane fuel tank ever manufactured. The two

wing tanks and the auxiliary tank hold 230 gallons each. Beside this, there is an oil tank holding 130 gallons of oil.

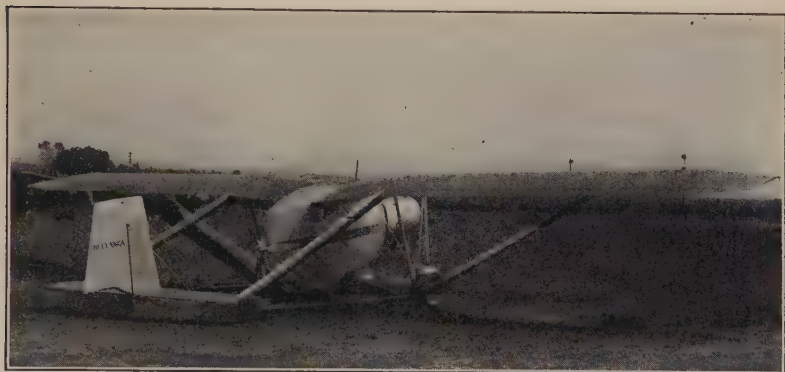


FIG. 151. Bellanca Tandem airplane or "Flying Gas-tank."

Initial performance tests on this machine give very promising results. The plane is capable of a very rapid take-off after a very short run. A low landing speed of 45 miles per hour is attained by using a large wing span, 87 feet, and by means of the 30-foot stabilizer attached to spars projecting from the upper and lower wings.

The power plant consists of two Pratt and Whitney "Wasp" engines mounted in tandem, giving a total of 840 horse power. The front engine drives a two-bladed steel propeller. The rear engine drives a three-bladed steel propeller, a pusher located behind the fuselage, by means of a hollow four-inch steel shaft extending through the fuselage. The cabin, which is stream-lined, narrows to a thin vertical edge at the rear.

Although this first model of this type of airplane is to be considered as an experiment, it is possible that such an airplane may be developed to carry freight or passengers in place of some of the gasoline which it is designed to carry at present.

The following chapter will be devoted to a description of the service instruments commonly in use in airplane operation.

CHAPTER XVII

AIRCRAFT INSTRUMENTS

With the rapid growth of aviation came the demand for instruments to measure how fast the airplane went, how fast it could climb, in what direction it was traveling, what its altitude was, what its inclination was in various directions and many other such details of airplane operation. The first instruments to be used were adaptations of instruments used in automotive, meteorological and marine work. The present chapter will be devoted to a discussion of the more common modern aircraft instruments.

Classification of instruments. ¹—Instruments used in aeronautics may be classified in three general groups, namely, *ground instruments* or instruments used solely on the ground, *aerological instruments* or instruments sent up in the air on kites or balloons solely for aerological purposes, and *aircraft instruments*, instruments installed on board navigable aircraft.

Aircraft instruments may, again, be subdivided into two classes as regards their use, namely, *experimental instruments* and *service instruments*. Experimental instruments include those instruments used for routine performance testing, steady, stunting and accelerated flight investigations, and for competitive altitude records. Service instruments for airplanes include all those instruments commonly installed in airplanes for determination of speed, altitude, direction, etc. The discussion in this chapter will be limited to those service instruments having to do with altitude, change of altitude, speed, direction and attitude determinations and those instruments necessary for proper observation of power plant operation. A typical arrangement of these instruments on the instrument panel is shown in Fig. 152.

¹ See National Advisory Committee for Aeronautics Technical Report No. 125.

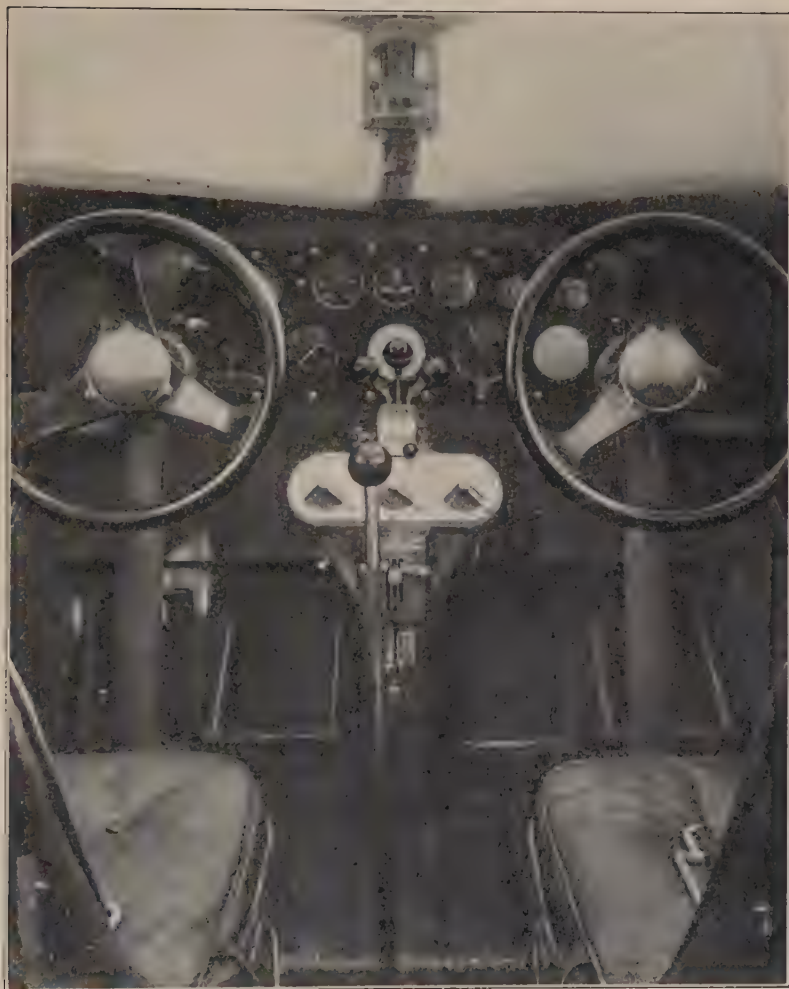


FIG. 152. Dual controls and instrument panel of Ford tri-motor transport plane.

ALTITUDE INSTRUMENTS ²

Altimeters. — An altimeter is an instrument used to determine the altitude of an airplane or an airship. The most common type of altimeter is a refined aneroid barometer with a scale calibrated to read altitude instead of pressure. Such an instrument is illustrated in Fig. 153.

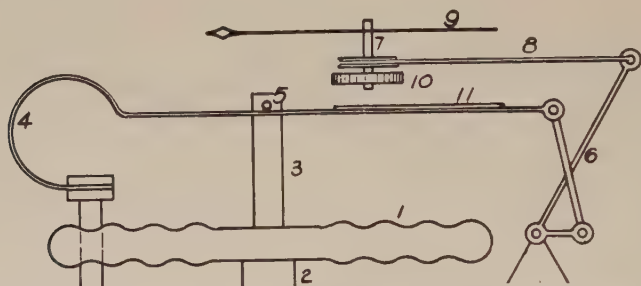


FIG. 153. A diagrammatic arrangement of an altimeter operating on the aneroid principle.

The pressure element or actuating element in this type of altimeter is a hollow chamber, cylindrical in form, with very thin walls. This element is evacuated to a very low pressure and sealed. Thus, the atmospheric pressure acting on the outside of the chamber tends to cause its collapse. This chamber is indicated at **1**, Fig. 153. To one wall of the chamber is fastened post **2**, which in turn is fastened rigidly to the altimeter case. To the other wall of the chamber is fastened post **3**, which is used to actuate the indicating mechanism. A D-spring **4** is so bent that when assembled it tends to separate the walls of the pressure element by pulling upward on post **3** by means of pin **5**. Thus, the D-spring carries part of the load on the pressure element caused by the atmospheric pressure. Any change in pressure causes motion of the pressure element walls with consequent motion of the free end of the D-spring. This motion is magnified by the linkage indicated at **6**.

² See National Advisory Committee for Aeronautics Technical Report No. 126; also "Aircraft Instruments" by H. N. Eaton.

One of the links is connected, by means of a small chain **8**, to the pointer spindle **7**. Thus, a change in pressure is indicated by a change in the position of the pointer **9**. This mechanism is kept under tension by means of spiral spring **10**.

Due to the expansion of the parts of the altimeter mechanism with change in temperature, the reading of the altimeter will be found to vary with temperature unless some compensating device is used. To compensate for temperature changes, one of the levers is usually made of two different kinds of metal **11**, with different temperature coefficients.

The dials on these instruments are usually adjustable so that the altimeter may be set at zero when starting a flight, regardless of what the pressure may be on that day. Altimeters are subject to errors due to changing barometric pressure during flight. If the barometer falls, the altimeter reading is greater than the true altitude; if the barometer rises, the altimeter reading is less than the true altitude. Likewise, if the destination of the flyer is at a different altitude or in a region of different barometric pressure than the field where he takes off, the altimeter will not indicate the true altitude above the landing field of his destination. One method of obviating this difficulty is to determine the barometric pressure at the pilot's destination, either by telephone or telegraph before taking off, or by radio while in flight, and to set the zero of the altimeter dial accordingly. It is particularly important for the pilot to know his correct altitude when the landing field is invisible, as when landing in the dark or in a fog.

Radio-echo altimeter. — The *radio-echo altimeter*, while still in the laboratory stage, appears very promising. This type of altimeter is actuated by reflected radio waves, originating in a radio set installed in the airplane. The reflected wave may be either in phase or out of phase with the wave sent depending on the distance from the ground to the airplane. The result is that, as the airplane changes altitude, whistling of the oscillating receiver passes through a complete tone cycle from a low pitch to a high pitch and back to a low pitch again, for every half wave-length

change in altitude. By counting the number of tone cycles passed through and multiplying by one-half the wave-length of the transmitter, the altitude can be very accurately determined. This method is particularly advantageous in that it measures the absolute altitude of the aircraft above the ground instead of altitude relative to a certain pressure level as does the aneroid type of altimeter. Since the transmitted wave is vertical, this type of altimeter does not indicate how far the aircraft is from an obstruction ahead, such as a mountain side. This difficulty may be overcome in the perfection of the instrument.

Barographs and altigraphs. — *Barographs* are instruments used for recording atmospheric pressure over a certain period of time. *Altigraphs* are instruments used for recording altitude or change of altitude over a certain period of time. The instruments differ only in that one has a scale graduated to read pressure and the other has a scale graduated to read altitude. The mechanism of the altigraph or barograph is shown diagrammatically in Fig. 154.

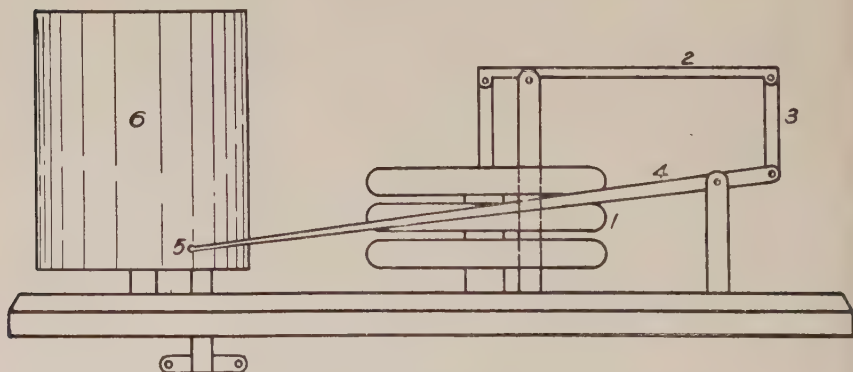


FIG. 154. Diagrammatic arrangement of a barograph or an altigraph.

Two or more pressure elements may be used to actuate the mechanism. These are shown at **1**. The motion of these elements with change in pressure is multiplied by levers **2**, **3** and **4**, lever **4**

having the pen **5** on its end. The drum **6**, which is driven by clock-work, has graduated paper on its surface. The pen records the change in altitude or pressure upon this graduated paper. A bi-metallic lever **2** is used for temperature compensation.

A barograph is used in recording altitude record attempts. These instruments are specially constructed and calibrated. The barograph indications, combined with temperature readings taken at different altitudes, are the data from which the altitude attained is computed by a prescribed method.³ The altitude thus computed is an arbitrary value because of the method of computing it. It may be as much as 1000 feet different from the true altitude attained by the pilot, depending on how close the actual conditions of flight compared to the conditions assumed for computing the altitude.

Bubble statoscopes. — *Statoscopes* are instruments used for detecting small changes in altitude or pressure. They are used when it is desired to maintain flight at a constant altitude or pressure level. They are of two principal types, the *bubble* type and the *mechanical* type. The bubble type statoscope is illustrated diagrammatically in Fig. 155.

It consists of a thermally insulated air chamber **1** with an outlet to the external air. Air passing to or from this chamber passes through a small radium-illuminated curved glass gage shown at **2**. A small amount of liquid of low density is placed in this curved glass gage. The enlarged portions at each end of the gage act as traps, preventing the liquid from being forced from the tube by the air flow.

A difference of pressure between the air in the air chamber and the external air causes the drop of liquid to move toward the end of the gage having the lowest pressure. As the drop enters the enlarged portion of the gage it forms a bubble. The bubble is pushed further into the enlarged portion of the gage, as the pressure difference is increased, finally breaking and allowing the liquid to flow

³ For methods of computing altitudes from these readings see "Aircraft Instruments" by H. N. Eaton, pages 13, 16, 17, 20 and 23.

back to the center of the tube as the air flows past to equalize the pressure. The liquid then acts as an indicating medium again. This

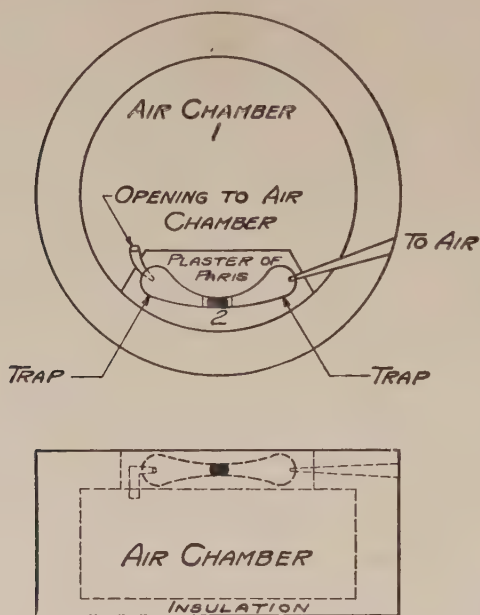


FIG. 155. Diagram of bubble statoscope.

cycle of operation continues as long as a pressure difference exists between the air chamber and the atmosphere. An increase in atmospheric pressure (decrease in altitude) causes the bubble to move to the left; a decrease in pressure (increase in altitude) causes the bubble to move to the right. The pressure or altitude change necessary to cause the bubble to move one of the arbitrary scale divisions of the instrument, must be determined experimentally. The sensitivity of the instrument is usually such that one scale division corresponds to a pressure change of 0.02 inches of mercury. At sea level, this corresponds to a change of altitude of about 20 feet. At an altitude of about 10,000 feet, it corresponds to an altitude change of about 26 feet.

Thus, one can tell, approximately, his change in altitude by noting the number of divisions passed over by the bubble. By noting the rate of bubble movement, the rate of climb or descent can be approximately determined.

Mechanical statoscope. — A mechanical statoscope is shown diagrammatically in Fig. 156. A corrugated diaphragm **1** is clamped to tightly cover an air chamber. The rubber hose **9**, providing connection to the atmosphere, has on it a pinch cock so that it may be closed at will. When it is desired to fly at a certain altitude, the pinch cock is left open until that desired altitude is attained, the statoscope reading zero during this time. When the desired altitude is reached, the pinch cock is closed. Any deviation from the desired altitude will cause a pressure difference on the two sides

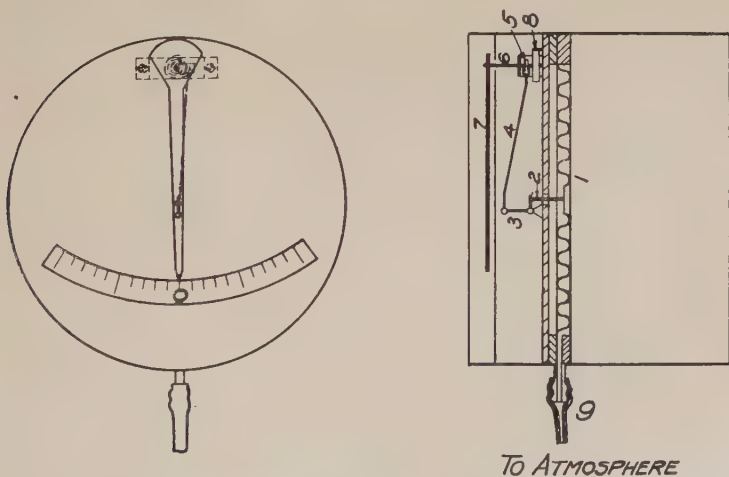


FIG. 156. Diagrammatic arrangement of mechanical statoscope.

of the corrugated diaphragm with a consequent deflection. This diaphragm movement is transmitted to the bell crank **3** by post **2**, soldered to the diaphragm. A link **4**, attached to the bell crank at one end and a cam **5** at the other end, causes the pointer **7** to move, the cam being fastened to the pointer shaft. The scale over

which the pointer moves has arbitrarily chosen divisions, the value of which must be determined by experiment. Unless thermally insulated, this type of instrument will be affected by change in temperature without change in altitude.

Climb indicator or vertimeter. — A *rate of climb indicator* or *vertimeter* is an instrument used to determine rate of change of altitude of an aircraft. One rate of climb indicator, called a *katano-scope*, consists of a mechanical statoscope as previously described, so arranged that the outlet to the external air can be opened and closed automatically at regular intervals. The reading of this type of instrument at the time of opening of the outlet valve is a measure of the rate of climb.

The most usual type of rate of climb indicator used for airplanes consists of a metal diaphragm, one side of which is directly con-

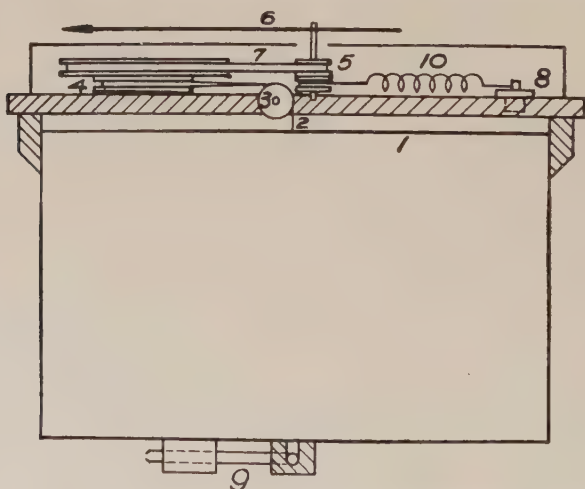


FIG. 157. Diagrammatic arrangement of capillary leak type rate of climb indicator.

nected to the atmosphere, the other side being connected to the atmosphere through a capillary leak tube. Such an instrument is illustrated in Fig. 157.

The top side of diaphragm **1** is exposed to the atmosphere. The under side is connected with the atmosphere only through the capillary leak tube **9**. When a change in altitude is taking place, the top side of the diaphragm is instantly under a new pressure. The pressure on the bottom side of the diaphragm changes more slowly, it being necessary for the air to flow to or from the air chamber through the capillary leak tube. The resultant pressure difference on the diaphragm causes it to deflect. This deflection is communicated to the indicating hand **6** by the phosphor bronze connecting strip **2**, which passes over pulley **3** actuating the multiple pulley **4**. Pulley **4**, being connected to pulley **5** by phosphor bronze strip **7**, causes the indicating hand to move. Backlash is prevented by helical spring **10**, which keeps the system under tension at all times. Zero adjustment is obtained by changing the position of block **8** to which the spring is fastened, thus changing the spring tension and the initial deflection of the corrugated diaphragm.

AIRCRAFT SPEED INSTRUMENTS ⁴

Aircraft speed instruments are of two distinct types with respect to airplane speed which they measure. One type measures the speed of the airplane relative to the air only and is called an *air-speed meter*. The other type measures the speed of the airplane relative to the ground and is called a *ground-speed meter*.

Pressure tube air-speed meters. — The most common types of air-speed indicators are the *Pitot* and the *Venturi* types. They are actuated by the pressure differences developed in suitably constructed nozzles when moved relative to the air. The manner in which the pressures change with airplane speed must be determined for each type of nozzle. The nozzle or nozzles are usually located on a wing or a strut away from the effect of the propeller slip-stream.

⁴ See National Advisory Committee for Aeronautics Technical Report No. 127; also "Aircraft Instruments" by H. N. Eaton.

The indicating device used with these pressure nozzles is a sensitive pressure gage, so calibrated that it reads air-speed instead of pressure difference. This indicating device is located on the instrument board of the airplane and is connected to the pressure nozzles by means of metal tubing. The pressure gage used for an indicating device may be a liquid manometer, a battery of corrugated capsules in an air-tight box, or a membrane diaphragm in an air-tight box.

As mentioned before, the pressure nozzles are of two types. The Pitot type consists of an open-ended pipe of uniform cross section, having its open end headed directly into the wind. The Venturi type consists of a tube flared at both ends, with a neck in between the flared ends. These pressure tubes may be used separately to actuate the indicating device or they may be used in some combination.

If the Pitot type tube, as shown at (a) Fig. 158, is used with a membrane diaphragm type indicator, the Pitot tube is connected to one of the air-tight compartments of the indicator and the static pressure tube is connected to the compartment on the other side of the diaphragm. Thus, the pressure on the side of the diaphragm to which the Pitot tube is connected is equal to the static pressure plus the impact pressure. The pressure on the other side of the diaphragm is the static pressure only. The difference of pressure, which causes the deflection of the diaphragm and the operation of the indicating mechanism, is equal to the impact pressure. Since this pressure varies with the square of the air-speed, the multiplying mechanism between the diaphragm and the pointer must be specially designed to permit the use of a uniformly graduated scale.

If the Venturi type pressure tube, as shown at (b) Fig. 158, is used, the tube connected to the Venturi throat is also connected to the compartment on one side of the diaphragm. The pressure on the side of the diaphragm to which the Venturi tube is connected is less than atmospheric or static pressure, because of the increase in velocity head at the Venturi throat. The pressure on the other side of the diaphragm is the static pressure. The diaphragm is

deflected by the difference between these pressures, the deflection being in the direction of the compartment to which the Venturi throat is connected. Again, a specially designed multiplying mechanism must be used in the indicating device to enable using a uniformly divided scale.

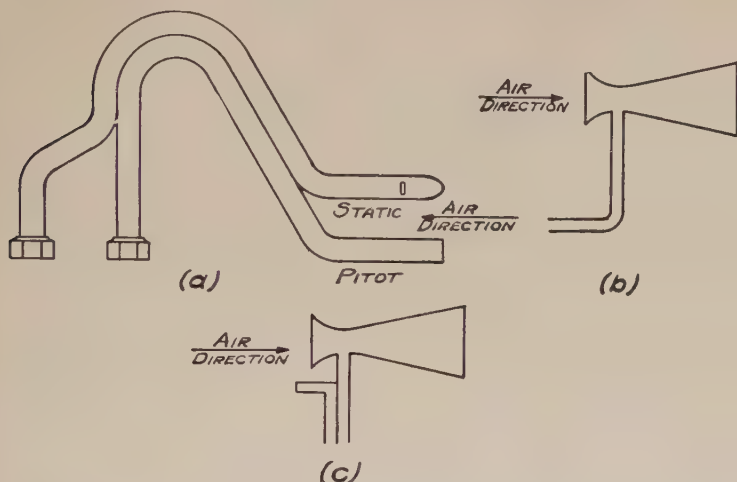


FIG. 158. Types of pressure nozzles used for air-speed measurement.

If a combination of Pitot and Venturi tubes, as shown at (c) Fig. 158, is used to actuate the indicator, the pressure causing deflection of the indicator diaphragm is the sum of the suction pressure in the Venturi throat and the impact pressure developed in the Pitot tube. Thus, a larger deflection for the same air-speed may be obtained with such a combination than could be obtained using either type of pressure tube alone; this means that a less delicate indicating device may be used. A disadvantage to this arrangement is that any partial obstruction, such as might be caused by ice, in the Venturi tube, will alter the instrument reading, whereas an instrument connected to a Pitot tube will read correctly until the Pitot opening is completely plugged. In any of the above arrangements, the instruments must be calibrated

to obtain the air-speeds equivalent to the pressure differences developed.

Anemometer type air-speed meters. — The instruments described in the preceding paragraphs are the ones most commonly used for measuring the air-speed of airplanes. Other types of instrument have been used to a smaller extent. Several of these are of the *anemometer* type, with either cups or small propellers mounted in the air-stream away from the propeller slip-stream. Some of these instruments are self contained, being connected to an indicating tachometer which must be read from a distance. Others of this type are of distant control, the tachometer element being caused to rotate in synchronism with the anemometer by current supplied through a synchronizing commutator connected to the anemometer shaft. The energy required to drive the tachometer is supplied from a battery or generator. Only the energy necessary to overcome friction is taken from the rotating anemometer.

Torque type air-speed meters. — Another type of instrument, which has been tried, consists of an anemometer cup or a flat plate carried on the end of an arm. The arm is fastened to a spindle and is prevented from turning about this spindle by means of springs. By suitable transfer mechanism, the deflection of the springs, which varies with the air-speed, is transmitted to the indicator. Since this type of instrument must be placed outside the propeller slip-stream, the indicator must be read from a distance by the pilot.

Hot wire air-speed meter. — The *hot wire air-speed* meter is an instrument depending for its action on the cooling of an electrically heated wire grid by the passing air. The effect of this cooling is to change the electrical resistance of the grid, and this, measured by a suitably calibrated instrument, serves to indicate the air-speed. This type of instrument has found considerable practical use in aeronautics abroad, and it is particularly adapted to certain labo-

ratory measurements. For a complete description, the reader is referred to treatises which deal with aircraft instruments in detail.

Effect of altitude on air-speed measurements. — All of the air-speed indicators mentioned have their readings influenced by variation in air density. Since air density decreases with altitude, it becomes evident that a correction must be applied for change in altitude. This correction is not as large as might appear at first thought, because density is determined not only by pressure, but also by temperature, and the two influences operate in directions which tend to nullify each other.

Ground-speed measurement. — In making long distance flights, in bombing operations, and in night or fog flying over courses not provided with beacons, it becomes very important to know the speed of the airplane relative to the ground in order to determine the position of the airplane at any time. In speed tests, such as the Schneider Cup Races, where the course is comparatively short, the ground-speed may be determined by observers stationed at various points on the ground. By taking the average of the times required by the pilot to fly over the course in opposite directions, the effect of the wind may be eliminated. The observers, who are stationed at each end of the course with stop watches for recording the times, must have their watches synchronized by telephonic or telegraphic communication before starting the timing.

The effect of the wind can also be eliminated by finding the time required to fly over the three legs of a triangular course. The difficulty with this method is in making sure the plane passes directly over the corners of the course.

The most difficult and the most important problem in ground-speed determination is the determination of the ground-speed of the airplane from the airplane itself. One type of instrument used, depends upon the pilot being able to see the ground, that is, it is an optical indicator and is therefore useless at night or in a fog. The optical type of indicator most commonly used depends upon determining with a stop watch, the time required for some stationary

object on the ground to pass between two sighting points on the ground-speed indicator, these points being in a horizontal line parallel to the longitudinal axis of the airplane. The ground-speed may be calculated if the altitude of the airplane, the distance from the observer's eye to the horizontal line determined by the sighting points, and the distance between the sighting points are known.

In Fig. 159, if the airplane is at position **1**, so that the object at **X** is in line with the observer's eye **E** and the forward sighting point, and then moves through a distance **B** to position **2**, so that the object is now in line with the observer's eye and the rear sighting point, in a time **t**, the ground-speed may be calculated as explained in the next paragraph.

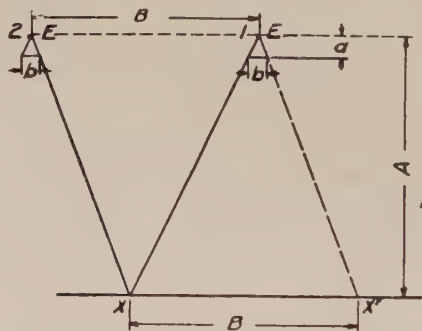


FIG. 159. Optical method of determining the ground-speed from the airplane.

An inspection of Fig. 159 shows that if we were to hold the airplane stationary at **1** and move the object **X** to a position **X'**, such that in its new position it would be in line with the observer's eye and the rear sighting point, it would have to be moved a distance **B**, equal to the distance the airplane would move to get the same result with the object stationary. From similar triangles we have

$$\frac{a}{A} = \frac{b}{B}$$

or,

$$B = \frac{b}{a} \cdot A.$$

Let S equal the ground-speed of the airplane. Then we have,

$$B = S \cdot t = \frac{b}{a} \cdot A$$

or,

$$S = \frac{b}{a} \cdot \frac{A}{t} = \frac{KA}{t}, \text{ K being equal to } \frac{b}{a}.$$

That is, the ground-speed of the airplane is equal to a constant times the ratio of the altitude of the airplane to the time for the object to pass the two sighting points.

Another method of determining the ground-speed of an airplane is by means of a rotating prism. If a hexagonal prism is mounted in a telescope, it is possible to rotate it at such a speed that the objects on the ground may be seen clearly through the telescope. The speed at which the prism must be rotated depends on the altitude and the ground-speed of the airplane. A dial on the instrument provides for setting at the correct altitude. Then the prism is rotated by means of a variable speed motor. When the objects on the ground appear plainly through the telescope, a tachometer attached to the motor reads the ground-speed.

As yet no other means of determining the ground-speed while in flight, except optical means, have been successful. Other means suggested are either dynamical or electrical. The dynamic method suggested is that of obtaining the time integral of displacement of a mass supported between springs so that it is free to move in a horizontal direction only. The integration would be proportional to the ground-speed of the airplane, since the displacements of the mass would be proportional to the accelerations of the airplane.

DIRECTION INSTRUMENTS

Need for compasses. — In flying between two points the airplane pilot must have some definite path to follow. In some instances such a course is easily followed, being along a river, shore,

or over some area with which the pilot is familiar. Transcontinental air mail routes are equipped with revolving beacon lights and directional radio beacons, both used to guide the pilot on his course. These will be described in a later paragraph. However, in flights over unfamiliar country, in night or fog flying, and in trans-oceanic flights where no land is visible, the only manner in which a pilot can keep on his course is by means of some sort of compass. There are three types of compass in use for aircraft. These are the *card magnetic*, the *earth inductor*, and the *gyroscopic* types. Because of its great weight, the gyroscopic compass is very seldom used on airplanes.

The card magnetic compass. — The card magnetic compass depends for its action on the earth's magnetic field. This field extends north and south around the earth and is approximately horizontal at the equator. At the magnetic North Pole and at the magnetic South Pole the field is vertical. At all places between the poles and the equator the field has both horizontal and vertical components. A free magnet suspended by its center will line itself up with the earth's field, provided there are no serious local magnetic disturbances.

The indicating element in the card magnetic compass consists of a card to which are attached several parallel magnets. This card, bearing the magnets, is so suspended by pivots within a suitable container that it is free to rotate in a horizontal plane. Thus, the magnets are free to assume the direction determined by the earth's field. The card is divided into quadrants and is marked with the cardinal compass points as is the dial of an ordinary compass. The north and south axis of the card coincides with the direction of the attached magnets. The container for the card is usually of glass, the indications of the card being read by means of a line on the glass container called the "lubber line." In installing the compass, the lubber line is made parallel to the longitudinal axis of the airplane, so that the compass reading will indicate the direction of the airplane's course.

The container for the card contains a damping liquid. This may be a mixture of alcohol and water or it may be kerosene. Kerosene

prevents the corrosion of the pivot points and is therefore considered superior to the alcohol and water mixture for a damping liquid ⁵. These compasses have an expansion chamber to accommodate changes in volume of the damping liquid with change in temperature.

Earth inductor compass. — The earth inductor type of compass is comprised of three distinct units. The actuating unit of the compass is the *inductor generator*. This unit consists of a rotating armature which reacts with the earth's field. It resembles the ordinary electric generator except that the magnets and their field are replaced by the magnetic field of the earth. Attached to the armature is a commutator and a set of brushes, which may be oriented about a vertical shaft. The amount of current obtainable from the armature depends upon the angle between the brushes and the direction of the field. As the brushes are shifted with respect to the field, there are found two positions of maximum current and two positions of zero current as with an ordinary generator. The positions of zero potential and current are utilized in the operation of this type of compass.

The second unit of the earth inductor compass is a *direction controller*. This carries a small dial divided into quadrants and degrees like an ordinary compass card. A crank, mechanically connected to the brushes of the generator, moves the brushes and the dial, the dial reading the direction in which it would be necessary to fly in in order to have zero current supplied by the armature.

The third unit of the compass is a sensitive galvanometer with a zero center. This is called a *steering indicator*. It is connected to the brushes of the generator.

In installing the compass, the connection between the direction controller and the brushes is made such that when the airplane is headed in the direction indicated on the controller dial, the brushes are in the position of zero current. Thus the galvanometer or steering indicator will read zero.

⁵ For other damping liquids, see National Advisory Committee for Aeronautics Technical Report No. 299, 1929, _

To use the compass, the desired heading is set by the pilot on the direction controller. When the airplane is headed in the proper direction, the steering indicator will read zero. Any deviation from the proper course will be indicated by motion of the steering indicator hand in the direction in which the deviation is made.

Radio beacons. — The radio beacon system is a system of directional radio control for airplane transportation. In this system, radio waves are transmitted alternately from two directive antennas arranged at right angles to each other. These signals are received on the airplane by means of an antenna and a simple receiving set. An indicator connected to the receiving set shows when the signals from the two directive beacons are received with equal intensity by means of two vibrating reeds, each of which is tuned to one of the modulated frequencies used by the two antennas at the transmitting station. The reed on the right is tuned to a frequency of 65 cycles per second and the one on the left to a frequency of 85 cycles per second. The tips of the reeds, which are white, are located on the panel against a black background. If the signals are being received with equal intensity, the vibrating reeds show as white vertical bands of equal length. If the white band on the right is the longer, the pilot is too far to the right and *vice versa*. When the pilot flies over the radio beacon, an indicator deflects suddenly, thus allowing him to determine the position of the beacon very closely.

The whole receiving outfit weighs only about 30 pounds. The same set can be used for radio telephone service by plugging in a pair of headphones.

Turn indicators. — A *turn indicator* is an instrument used for indicating deviation of an aircraft from straight line flight. It indicates the presence of a yawing velocity. Most turn indicators are of the gyroscopic type. They consist of a small gyroscope rotating about a horizontal shaft. The gyroscope is mounted in a cradle so that it is free to precess in one direction, thus being unaffected by rolling or pitching. Its mounting is somewhat as shown in Fig. 160.

The torque of procession is resisted by a spring, the spring deflection being indicated on a dial. The gyroscope may be electrically

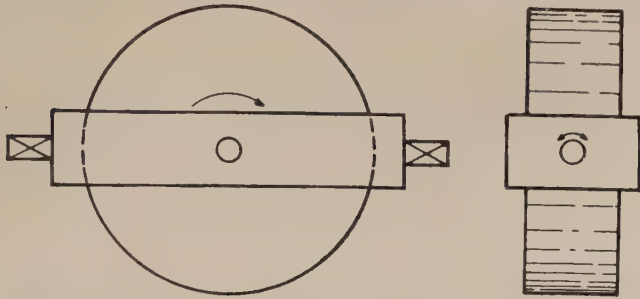


FIG. 160. Diagrammatic arrangement of gyroscope mounting for use as a turn indicator.

or air driven. In one type of instrument, the vacuum secured with a Venturi tube is used to produce an air-stream which impinges directly on the serrated edge of the gyroscope rotor.

Inclinometers. — An instrument used to determine the attitude of an airplane is called an *inclinometer*. If the inclinometer is used to determine the attitude of the airplane about its pitching axis, the instrument is called a *pitching indicator*. If used to determine the attitude about the rolling axis, it is called a *lateral inclinometer*.

Inclinometers may be divided into two classes, those showing the attitude of the airplane with respect to the true zenith, called *absolute inclinometers*, and those showing the attitude relative to the resultant of the acceleration of the aircraft and that of gravity, called *relative inclinometers*.

Absolute inclinometers. — Absolute inclinometers are practically all of the gyroscopic type. They consist of a gyroscope with a vertical spinning axis, mounted on a pendulum, which in turn is so mounted that it has two degrees of freedom. Rolling or pitching during steady flight leave the axis of the gyroscope vertical, the pendulum remaining vertical under the action of gravity. If the rolling and pitching are accompanied by linear

acceleration of the airplane, the bob of a simple pendulum will move immediately in the direction of the acceleration, causing the reading of inclination of the airplane in the plane of the acceleration to be in error. The gyroscopic pendulum, if subjected to the same conditions, will move slowly and with a smaller amplitude **at right angles to the acceleration**, thus leaving the indication of inclination in the plane of the acceleration undisturbed.

Relative inclinometers. — Relative inclinometers are of several different types. In one type, known as the *rolling ball inclinometer*, a ball of steel or some like material is contained in a curved glass tube filled with oil, alcohol, or glycerine as a damping fluid. This tube is mounted with its plane in the direction in which the inclination of the airplane is desired. The position of the ball, which is under the influence of the acceleration of the plane and the acceleration of gravity, indicates the inclination of the airplane relative to the resultant of these accelerations.

In the *pendulum type of relative inclinometer*, a pendulum is mounted with freedom in the direction in which a knowledge of the inclination is desired. To prevent continued oscillations, the pendulum may be damped by immersing it in a liquid, or it may have a dash pot attached for damping purposes. A damped pendulum inclinometer is shown diagrammatically in Fig. 161 at (a).

In the *bubble type of relative inclinometer*, the action is similar to that of a rolling ball instrument, except that the ball is replaced by the bubble and the glass tube is curved the opposite way, as in a carpenter's level. The liquid used in this instrument is oil, alcohol, or a mixture of alcohol and glycerine.

In the *liquid type of relative inclinometer*, the indication is obtained from the level of a liquid contained in some sort of glass container. The shape of this container varies with different manufacturers. In one type of liquid instrument, the case is a thin circular container mounted in a vertical plane, the readings being obtained by indicating lines on the container and the level of the liquid. Most other types of liquid inclinometers consist

of liquid in an endless circuit of glass tubing, some of the legs of the circuit having graduations on them so that the inclination of the airplane can be read by the position of the liquid meniscus relative to these graduations. Such an instrument is shown diagrammatically at (b) Fig. 161. The necked portions of the tubing damp the fluctuations in the meniscus level.

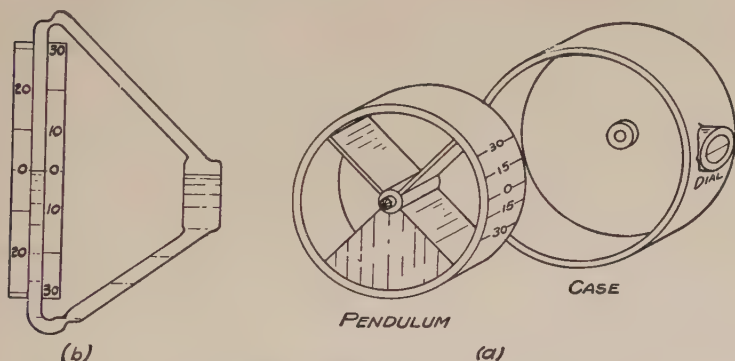


FIG. 161. Diagrammatic arrangements of pendulum and liquid type relative inclinometers.

Pitching indicators. — A *pitching indicator* is an inclinometer used to determine the pitching attitude of an airplane. They are usually of the gyroscopic type previously described in the section on inclinometers.

Banking indicators. — A *banking indicator* is an instrument used to detect departure of the airplane from the correct banking angle for the radius of turn and speed at which the airplane is flying. When an airplane is turning at the proper banking angle, the resultant of gravity and the centrifugal force is very nearly perpendicular to the floor of the airplane. Consequently, any type of relative inclinometer used as a lateral inclinometer should read zero at that time. Because of this, the relative inclinometer is used for a banking indicator. When used in this manner, the indicator does not show the absolute inclination with respect to the earth. In fact, it is not used to measure inclination but to determine

the proper banking angle. Any departure from the correct banking angle causes an indication on the banking indicator. Otherwise it reads zero regardless of the lateral inclination of the airplane relative to the ground.

Yawmeters. — A *yawmeter* is an instrument used to determine the angle of yaw of an airplane, that is, the angle between the longitudinal axis of the plane and the flight path. This instrument

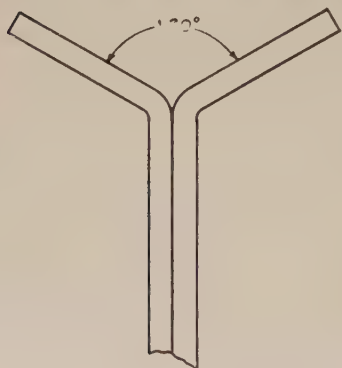


FIG. 162. Head of a yawmeter.

consists of a pair of open mouthed tubes adjacent to each other, but so bent that the included angle between them is about 120 degrees, as shown in Fig. 162. These tubes are mounted in a plane parallel to the floor of the airplane, and symmetrically with respect to the longitudinal axis of the airplane. If the angle of yaw is zero, that is, if the tubes both meet the air at the same angle, they will both have the same

pressure induced in them. If the angle of yaw is not zero, the tube which heads the more directly into the wind will have the greater pressure induced in it.

By means of flexible diaphragms and magnifying levers, the differential pressures obtained in the two tubes are made to actuate an indicating pointer which moves over a scale calibrated to read the angle of yaw.

POWER PLANT INSTRUMENTS ⁶

Tachometer. — A *tachometer* is an instrument used to determine the rotative speed of the propeller or of the engine shaft of an

⁶ For detailed description of construction, calibration, and testing of these instruments, see National Advisory Committee for Aeronautics Technical Report No. 129; also "Aircraft Instruments" by H. N. Eaton.

airplane or the speed of rotation of any rotating member of any machine. An *airplane tachometer* is a specially designed instrument used for the former purpose. Since any kind of engine trouble results in a reduction of engine and propeller speed, the tachometer is useful as an indicator of engine performance. It also enables the pilot to run his engine at the speed of maximum efficiency or maximum economy, if he so desires.

There are six principal types of airplane tachometers, namely, *chronometric tachometers* which measure rotative speed by recording the amount of motion of some part in a fixed time interval, *centrifugal tachometers* which indicate speed by the amount of deformation of a spring caused by a rotating weight, *air viscosity tachometers* which act by the viscosity of a thin air film flowing between two concentric cylinders, *air pump tachometers* in which speed is indicated by the pressure developed by an air pump operated at a speed proportional to the engine speed, *magnetic tachometers* which depend on the electromagnetic induction between a revolving magnet and a conducting drum or disk, and *electric tachometers* consisting of a magneto or generator connected to a voltmeter calibrated to read the speed in revolutions per minute. Tests made on the various types of tachometers have shown that the chronometric and centrifugal types were superior to the other types as to accuracy under varying conditions of temperature and pressure.⁷ Of these two types the chronometric is the slightly more accurate but not so durable as the centrifugal type.

Chronometric tachometer. — In the chronometric tachometer, speed is measured by the motion of a gear or of a toothed rack, connected to the main drive, for equal intervals of time. These equal time intervals are regulated by an escapement mechanism. Since the time intervals are equal, the motion of the gear or rack during the interval is proportional to the average speed of the engine during the interval. It may therefore be used as a measure

⁷ See National Advisory Committee for Aeronautics Technical Report No. 129, 1922.

of the speed. The motion of the gear or rack is shown by a pointer moving over a dial graduated in revolutions per minute. At the end of the equal time intervals, the pointer jumps to a new position to indicate a change in speed.

Centrifugal tachometers.— In this type of tachometer, the actuating mechanism is a weight or weights rotating about a shaft, as in a fly-ball governor. Such an instrument is illustrated diagrammatically in Fig. 163.

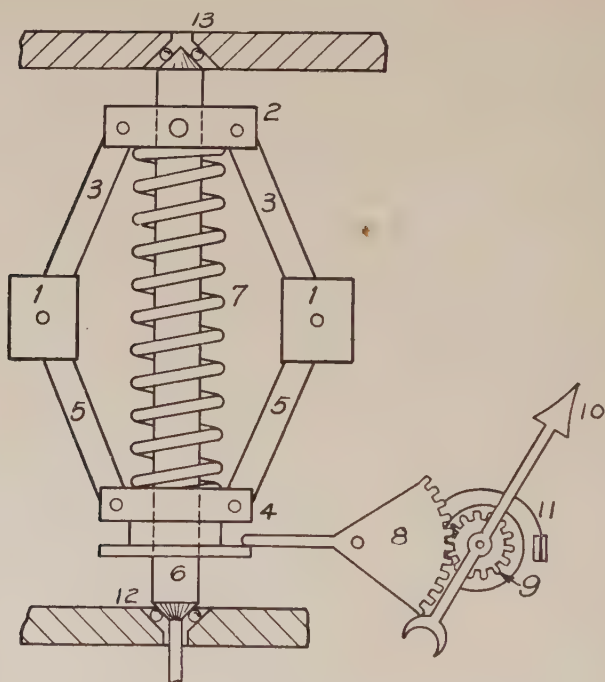


FIG. 163. Governor type of centrifugal tachometer.

The weights 1, suspended from collar 2 by links 3 and fastened to collar 4, which is keyed to the shaft 6 but free to move vertically on it, by links 5, tend to fly away from vertical shaft 6 when rotated. As they go away from the shaft, collar 4 is pulled upward

by the linkage. The motion of the collar **4** and therefore the motion of the weights, is opposed by spring **7**. The motion of collar **4** is a measure of the speed of rotation of shaft **6**. The motion of collar **4** is transmitted by means of the lever and gear sector **8** to the gear **9** which is fastened to the spindle carrying the indicating pointer **10**. The indicating mechanism is kept under tension at all times by spiral spring **11**. Shaft **6** is of hardened steel and rotates in ball bearings **12** and **13**. An extension of shaft **6** is provided with means for connection to the engine or propeller shaft. Pointer **10** moves over a scale calibrated to read revolutions per minute.

Air and oil pressure gages. — *Pressure gages* are used on airplanes to measure the air pressure in the gasoline tank and the pressure in the oil supply system. When a pressure system is used, operation of the engine is dependent on there being enough pressure in the gasoline tank to force the gasoline to the carburetor. The life of the engine is dependent upon a constant supply of oil to all the important bearings and rubbing parts. Thus, gages for measuring the air and oil pressures are of importance for insuring proper operation and maintenance of the airplane engine.

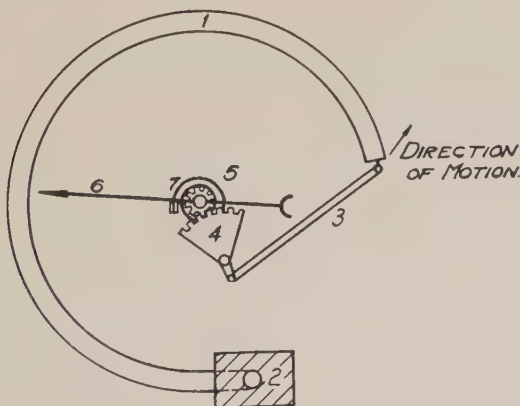


FIG. 164. Diagrammatic arrangement of Bourdon tube type pressure gage.

Most of the gages used for airplane work are of the Bourdon tube type. A *Bourdon tube* is a flat hollow tube bent in a circle arc. It is the actuating element of the pressure gage. A gage of this type is shown diagrammatically in Fig. 164. The Bourdon tube shown at **1** is solidly fixed at one end by the block **2** which in turn is fastened to the gage case. The pressure is introduced into the tube by means of the pipe connection in block **2**. The pressure acting on the inside of the tube causes it to straighten out slightly, causing deflection of the free end in the direction indicated. This motion is transmitted, by link **3** and gear sector **4**, to the pinion **5** on the pointer shaft. The pointer **6** moves over a scale calibrated to read pressure. Spiral spring **7** prevents backlash and keeps the system under tension continuously. Change in pressure range is effected by changing the Bourdon tube for one of different stiffness and by using a scale properly calibrated for the new tube.

Gasoline depth or level gages. — In flights of any distance, it is important to know the depth of gasoline in the fuel tanks so the amount of fuel remaining can be estimated. Many different mechanical means are used to operate the indicating mechanism of the depth gage. Sometimes an ordinary pressure gage is connected to the bottom of the fuel tank, the pressure varying as the depth of the fuel in the tank. The most common type of fuel level gage consists of a float, connected by means of a cord or flexible wire and drum, by levers, by gears, or by a twisted metal strip to the indicating dial. The rise or fall of the float, thus, is transmitted to and indicated on the fuel level dial.

Fuel flow-meter. — A fuel *flow-meter* is used to determine the rate at which gasoline is being used by the engine. These instruments are also called *econometers*. In one type of flow-meter, shown at (a) Fig. 165, gasoline flows up into the center tube and out through a narrow slit in the side into the annular space between the outer and inner tubes. Within the inner tube is a plunger which takes up a position such that the fluid force exerted on its base is equal to its weight, thus making the volume of gasoline flowing through

the slot directly proportional to the length of the slot. A pointer on the plunger, extending through the slot in the inner tube, is visible through the outer glass tube.

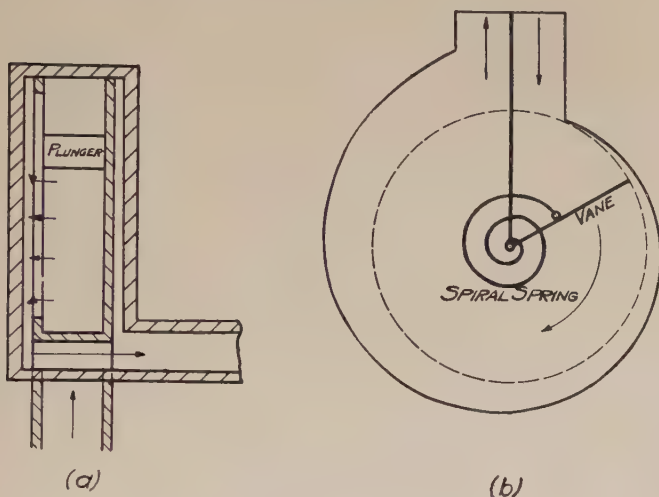


FIG. 165. Two types of fuel flow-meters.

The type of flow-meter shown at (b) Fig. 165 consists of a vane pivoted at the center of a spiral casing. The opening in the casing is not entirely obstructed by the vane, fuel going between the end of the vane and the casing. The farther the vane swings in a clockwise direction, the greater is the unobstructed opening. Thus, for every rate of flow there will be a definite vane position. A pointer attached to the vane spindle will indicate the rate of flow when used with a properly calibrated scale.

Engine thermometers. — Engine thermometers are very useful in airplanes for determining if the engine is over-heating or if it is at such a low temperature that the cooling water might freeze or the oil and grease might congeal giving improper lubrication. These last conditions might obtain during long glides in cold weather or in glides from high altitudes.

An airplane engine thermometer must be distant recording, it

must be unaffected by large temperature and pressure changes, and it must be such that the tube connecting the thermometer to the indicator does not have to be at the same temperature throughout its length in order to give proper readings. The instrument must also be light, strong, and simple in construction.

These thermometers are of two general types, the *electrical* and the *pressure* types. The electrical type has not gained popularity in this country because of its greater complexity, costliness, and weight.

A *pressure thermometer* consists of a bulb, containing a liquid or a gas or both, connected by means of capillary tubing to a pressure gage. If the quantity of liquid is such that there is always a free surface in the bulb, the remainder of the tube and gage being filled with vapor, the thermometer is called a *vapor pressure thermometer*. If the tube, gage, and bulb are completely filled with liquid, the thermometer is called a *liquid filled thermometer*.

Vapor pressure type thermometer. — In the vapor pressure type thermometer, the vapor pressure depends solely upon the temperature of the free surface of the liquid in the thermometer bulb. Thus the gage connected to the bulb may be calibrated to read temperature instead of pressure. The scale obtained by such a calibration is not uniform.

Liquid filled thermometer. — In the liquid filled thermometer, the thermal expansion of the liquid in the bulb is utilized to operate the pressure gage. Since the thermal expansion of the alcohol used in these thermometers is almost a linear function of temperature for the range of 0° to 100° Centigrade, the scale on this type of thermometer is more nearly uniform than that of the vapor pressure type.

The following chapter will be devoted to a discussion of the outstanding aviation problems of today.

CHAPTER XVIII

OUTSTANDING PROBLEMS IN AVIATION

Early problems. — The first problem in airplane flight was to obtain sustentation. This required an airplane engine with sufficient power and not too great weight. The development of the gasoline engine solved this problem. Next were the problems of stability and control, and much inventive skill has been shown in their solution. Although improvements in obtaining sustentation, stability and control may be expected, the principal problems in this field have been solved, so that airplane flight is far beyond the experimental stage and is now well established as a practical means of transportation. There are still, however, many problems, connected in the main with safety, which must be solved to insure more dependable use of the airplane under all conditions of weather.

Present problems. — Ability to fly in fog, or so-called *blind flying*, and the *prevention of ice formation* are two of the major problems today. Related problems are those of the transmission of information as to location and weather. They are complex and involve many subsidiary problems, in the solution of which considerable progress has already been made. Complete and satisfactory solutions will assure the continued rapid growth of airplane transportation, the airplane then becoming as independent of weather as craft on land or sea.

Blind flying. — Visibility in heavy fog or snow is almost nil. Hence blind flying is essential. This means that the pilot must be able to take off, keep on his course, maintain the right altitude on that course, avoid collision, locate the port at which he wishes to land and make a safe landing solely by dependence upon his instruments.

The possibility of blind flying was demonstrated¹ in September, 1929, by Lieut. J. H. Doolittle who took off, flew away and, after several turns, came back and landed, while seated in a completely covered cockpit.

For blind flying to become established in service, existing instruments (some of which are described in the preceding chapter) must be perfected and new instruments be developed, so that all essential information is readily at the pilot's command.

Simplification is desirable in individual instruments and in the whole system of instrumentation as well. Time lag and errors in instruments due to inertia should be reduced to a minimum.

Automatic pilot. — Operation of the controls may be made *automatic* without the intervention of the human hand, and much has been done in developing automatic piloting devices for this purpose. There are, however, differences of opinion as to their desirability. A human mind anticipates certain conditions whereas an automatic device, unless very elaborate, does not correct for them until after they actually occur. An automatic pilot, therefore, tends to over control, and does not reverse the control until *after* the airplane passes through its correct position.

On the other hand, a human pilot is biased by his feelings, which may not be so correct in blind flying as the indications of his instruments. Placing confidence in feelings rather than in instruments under these circumstances may lead to disaster. Again, the pilot may become confused when he has too many instruments to watch. This points toward a compromise, namely, relieving the pilot of certain controls, as staying on a straight course and maintaining altitude by means of a gyro or other automatic device, leaving him the responsibility of turning and landing.

For blind flying, either with or without an automatic pilot, a reasonable amount of surplus power is highly desirable and also sufficient (but not too much) inherent stability about all three

¹ Under the auspices of the Daniel Guggenheim Fund for the Promotion of Aeronautics; see report "Solving the Problem of Fog Flying," upon which some of the following statements regarding blind flying are based.

axes, at low as well as at high speeds, independent of whether the throttle is on or off.

Altitude determination. — Barometric altimeters are at present the only ones fully developed and usable, but they show altitude above sea level (not above ground), are subject to error with sudden change in angular position of the airplane and to errors due to oscillation and to time lag, as well as errors due to change in meteorological conditions, unless the pilot is kept informed of these by radio so as to keep his instrument corrected for ground level. For a satisfactory determination of absolute altitude above ground, it seems that we should look to radio-echo or sound-echo methods.

Both methods are subject to disturbance from noise and vibration of the airplane and, in some cases, from engine ignition.² Several variations of these two methods are under development. An objection, not insurmountable, to any sound method is the fact that sound may be reflected from other surfaces than the ground directly beneath the airplane and may be slightly refracted, so as not to travel in a straight line. To a lesser extent, the same is true of radio methods. To minimize³ weight of accessory apparatus is of utmost importance.

In landing, an exact knowledge of absolute altitude is essential; an error of a few feet, insignificant when flying high, may then cause a crash. A practical device, although probably not the final answer, is a suspended weight that indicates to the pilot when it strikes the ground or causes the airplane to nose up. In an emergency, parachute flares may be dropped to give visibility.

Collision. — The most serious danger due to lack of visibility is collision with some moving aircraft or with a fixed object. Collision with a fixed object, as a mountain, can be avoided if its distance can be determined, as by echo methods used in the deter-

² Disturbance from engine ignition may be avoided by proper shielding. Such disturbance does not exist with the Diesel motor.

³ The weight of a special oscillator as a source of sound in the sound-echo method could be saved by using in its stead some source of sound already present in the airplane.

mination of absolute altitude. The danger of collision with another aircraft may be lessened by traffic rules and by means for indicating its proximity. The most promising way of accomplishing this is based on the difference in time taken to receive echoes from a radio signal and a simultaneous sound signal.

Direction and position. — The magnetic compass is subject to error due to lag and oscillation, during sudden maneuvers and to a so-called northerly turning error, unless a turn indicator is also used. The problem of direction finding has, however, a fairly satisfactory solution in the earth inductor compass, described in the preceding chapter. It is easy to use, since it only involves setting the direction controller for the desired course and keeping the steering indicator at zero. That it is sufficiently accurate is evidenced by its successful use on six different trans-oceanic flights and one flight to the North Pole. Because of the surprisingly good results already obtained with this type of compass, it is felt that, possibly with some further development, it may solve the direction-finding problem.

Experiments with a gyro-compass show that it may aid in making a turn or in holding a course for a short time; thus far, it is not so satisfactory for long flights. The radio beacon is very satisfactory for flying over a fixed air route. Interference with other beacons or stations and static interference limits its satisfactory range to about one hundred miles.

Radio bearings and position, calculated by triangulation from the direction of radio signals from the airplane received by two or more ground stations and communicated by radio to the pilot, are at times satisfactory at distances not over one hundred miles. At other times they are quite unreliable due to erratic directional changes in radio signals.

An electrified cable, surrounding or leading to a landing field and carrying an alternating current which is detected in the airplane, has been used with some success, but requires considerable power and, unless the method is more fully developed, does not give the pilot all of the desired information.

Penetration of fog. — Fog is not sufficiently penetrable by light radiation to make such radiation available for blind flying. Red radiation does not possess the greater penetration compared with white light as commonly supposed, although it is true that in a fog, a red light, *when it penetrates*, is more readily distinguished than a white or blue light, on account of less scattered or diffused light to obscure it. The proposed use of infra-red signals from a landing field, to be received by sensitive receiving devices on the airplane, seems feasible only at small range.

Sound signals, in or beyond the audible range, have a promising future. The best frequency is to be determined. Such signals, however, are open to the objection, already pointed out, that they are reflected and refracted and their direction is uncertain.

Radio signals are very satisfactory. Here, again, the best frequency is to be determined.

Fog prevention and dissipation. — Although the abatement of smoke nuisance reduces the fog over cities, no way is known of reducing fog or preventing it entirely over large areas. On a small scale, fog can be precipitated by the scattering of electrically charged particles of water or sand. Dissipation of fog by heat, by mechanical churning or by the use of drying agents, on any adequate scale, is practically impossible.

Ice formation.³ — When subjected to certain atmospheric conditions, airplane wires, struts, wings, propellers and certain instruments become so coated with ice as to make sustentation impossible. The wires are the first parts to be affected, the ice coating causing them to vibrate noticeably. The struts and various instruments, such as Pitot or Venturi heads, are the next members to be affected. Lastly, the leading edges of the wings and sometimes of the propeller become coated with ice. During the formation of the ice, various parts are felt to vibrate, the vibrations

³ For a review of work on ice formation, see National Advisory Committee for Aeronautics, Technical Notes, Nos. 293 and 306.

affecting first one part of the machine and then another as the amount of ice increases.

The machine under these conditions squashes forward, the drag being increased so much that the lift-drag ratio is reduced below that necessary for steady flight. The result is a forced landing unless a region of air, warm enough to melt the ice, is attained.

Hard ice due to heavy fog or rain. — One of the conditions under which ice forms is that of heavy fog, clouds or rain with a temperature of from 29° F. to 32° F., a very narrow temperature zone. Prevalence of this condition will cause a forced landing in from a few minutes to a half-hour. The more free water the more rapid is the formation of ice. The condition where rain falls from a stratum of warmer air into a stratum of air at a temperature below 32° F. is ideal for the formation of ice.

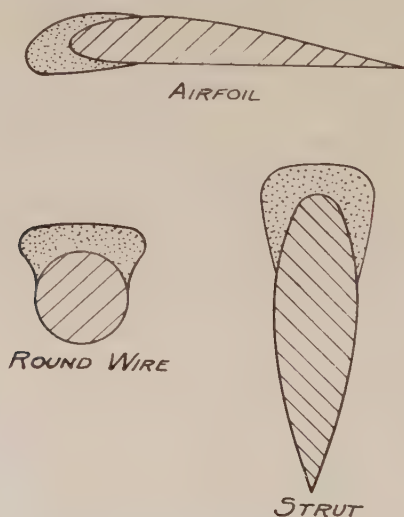


FIG. 166. Shape of hard ice deposits on airplane parts of different contour, due to heavy fog or rain.

The ice forming under these conditions is very hard and clear and is known as *hard ice*. The shapes of the deposits collected on members of various shape are shown in Fig. 166. These bulging

ice deposits not only add weight but, what is more serious, reduce the aerodynamic efficiency of the wing by decreasing lift and increasing drag, as well as increasing the drag of wires and struts. Compare these shapes with the shapes shown in Fig. 168, computed by Merit Scott from certain theoretical considerations.

Rime ice due to fine fog. — Another condition under which ice forms is that of an atmosphere containing undercooled fog particles at a temperature of from 20° to 10° F. and lower. This is a wide temperature range, definitely outside of the narrow temperature zone for hard ice. The ice formed under this condition is softer than hard ice and not so heavy for the same volume, being white like snow or hoar frost. It is called *rime ice*. The shape of the deposit of rime ice, as shown in Fig. 167, shows no

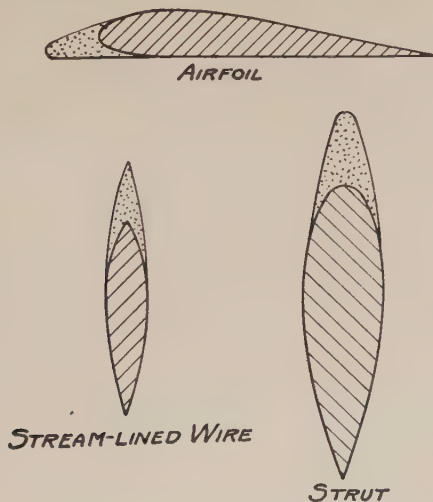


FIG. 167. Shape of rime ice deposits on airplane parts of different contour, due to fine fog particles.

tendency to “mushroom,” as in the case of hard ice, and does not so materially increase the drag. Unless the original member were perfect, rime ice might initially even aid, rather than detract from, its aerodynamic efficiency. It is interesting to compare

the forms of rime ice deposits in Fig. 167 with the computed formation in Fig. 169.



FIG. 168 Computed shape of hard ice deposit for non-turbulent and turbulent air flow around a symmetrical member.

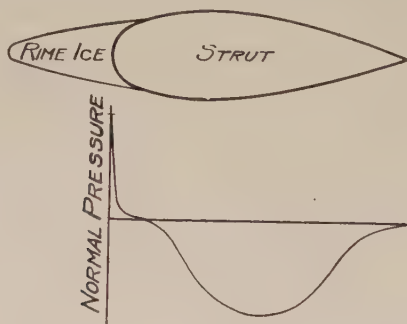


FIG. 169. Computed shape of rime ice deposit, where pressure is positive.

Preventing ice formation. — Reducing or eliminating wires and struts is a possible means for eliminating a part of the problem. Most important is the prevention of ice formation on the leading edge of the wings. Local heating electrically or from the exhaust is an obvious possibility, but thus far not satisfactory. Heat must be controlled so as to be adequate and yet do no damage. Furthermore, heating only the leading edge seems merely to shift further back on the wing the place where ice forms; while heating the entire wing is a difficult undertaking. Any equipment used for preventing ice must not add too great weight, an objection to some methods for ice prevention which otherwise might be feasible.

An oily surface, while seemingly promising, develops the unexpected fact that it frequently increases rather than decreases the formation of ice, as the particles of water, driven at high velocity,

become imbedded in it and freeze, without rolling off as would water at low velocity. This might be avoided by the use of a hard substance, with the properties of grease, in which the particles of water would not be imbedded.

A coating with the properties of salt to reduce the freezing point, also, opens possibilities. There is the tendency, however, for any surfacing to wash off. Furthermore, the quantity of salt or other chemical necessary for an extended flight seems prohibitive.

Ice removal. — The two primary requirements for the removal of ice are: first, low ice adhesion; second, means for breaking the vacuum between the ice and the surface. A pneumatic nose, which has been developed to meet these two requirements, proves to be an important step toward the elimination of the ice hazard.

Made of flexible material with low ice adhesion, the surface of the pneumatic nose is periodically distorted by means of internal ducts connected to a pulsating source of air pressure. These distortions break the vacuum and, when the nose is properly designed, allow the ice to be blown away. A pneumatic nose constructed of rubber was given a successful trial at Cleveland, Ohio, early in 1930, by the National Air Transport, Inc. When other parts of the plane landed coated with ice, those parts equipped with this device were ice free.

High altitude and high velocity transport. — As already pointed out, the aerodynamic conditions for fast flight are found at high altitude, due to lesser air density and decreased drag. Despite this fact and despite the fact that altitudes of five or six miles or more are frequently attained, most transport flight has been relatively near the ground. Lindbergh's flight from coast to coast in April, 1930, at an altitude between 10,000 and 15,000 feet, at a velocity over 170 miles per hour, made to test the possibility of commercial routes at high altitude, points towards the possibility of flights at still higher altitudes and greater velocities.

Weather. — The airplane has the atmosphere as its right of way or highway. The atmosphere may be clear or foggy, calm or stormy, moist or dry, but its condition cannot be controlled, as the right of way of a railroad or a highway for automobiles. For mail service and transport, where schedules must be met and where valuable property and human lives must be safeguarded, it is essential, therefore, that the pilot be aware of weather conditions over the route he must follow.

Daily or twice-daily weather reports from stations far apart are inadequate. That atmospheric conditions may be ascertained and future conditions predicted, meteorological observing stations must be situated at close intervals and must be interconnected by telephone or telegraph so that regular reports, perhaps hourly, may be collected by some central office, arranged in some convenient form for use for the pilot and communicated to him.

Such a system was installed for the guidance of pilots operating on the San Francisco-Los Angeles transport routes early in 1928, resulting in remarkable freedom from accident. Like service has since been extended to other aerial highways. It should become nation-wide or world-wide in scope. Thus, although the weather cannot be controlled, the pilot can be warned in advance of conditions ahead or informed while in flight, and can be advised at times of means for avoiding adverse conditions.



APPENDIX

GLOSSARY¹

absolute inclinometer — See INCLINOMETER, ABSOLUTE.

accelerometer — An instrument for indicating, measuring, or recording accelerations.

aerodynamics — The branch of dynamics which treats of the motion of air and other gaseous fluids and of the forces acting on solids in motion relative to such fluids.

aeronautics — The science and art pertaining to the flight of aircraft.

aerostat — A generic term for aircraft whose support is chiefly due to buoyancy derived from aerostatic forces. The immersed body consists of one or more bags, cells, or other containers, filled with a gas which is lighter than air.

Syn. — LIGHTER-THAN-AIR CRAFT. Includes airship and balloon, q. v.

aerostatics — The science that treats of the equilibrium of gaseous fluids and of solid bodies immersed in them.

As an aeronautic term, it relates to those properties of lighter-than-air craft which are due to the buoyancy of the air.

aileron — A hinged or pivoted movable auxillary surface of an airplane, usually part of the trailing edge of a wing, the primary function of which is to impress a rolling moment on the airplane.

aileron angle — See ANGLE, AILERON.

air controls — See CONTROLS.

aircraft — Any weight-carrying device or structure designed to be supported by the air, either by buoyancy or by dynamic action.

airfoil — Any surface designed to be projected through the air in order to produce a useful dynamic reaction.

airfoil section (or profile) — A cross section of an airfoil made by a plane parallel to a specified reference plane. A line perpendicular to this plane is called the axis of the airfoil.

air log — An instrument for measuring the linear travel of an aircraft

¹Taken from "Nomenclature for Aeronautics," Report No. 240 of the National Advisory Committee for Aeronautics.

relative to the air. One form consists of a windmill with a revolution counter.

airplane — A mechanically driven aircraft, heavier than air, fitted with fixed wings, and supported by the dynamic action of the air.

airplane, pusher — An airplane with the propeller or propellers in the rear of the main supporting surfaces.

airplane, tandem — An airplane with two or more sets of wings of substantially the same area (not including the tail unit) placed one in front of the other and on about the same level.

airplane, tractor — An airplane with the propeller or propellers forward of the main supporting surfaces.

airport — A locality, either of water or land, which is adapted for the landing and taking off of aircraft and which provides facilities for shelter, supply, and repair of aircraft; or a place used regularly for receiving or discharging passengers or cargo by air.

airship — An aerostat provided with a propelling system and with means of controlling the direction of motion. When its power plant is not operating, it acts like a free balloon.

nonrigid — An airship whose form is maintained by the internal pressure in the gas bags and ballonets.

rigid — An airship whose form is maintained by a rigid structure.

semirigid — An airship whose form is maintained by means of a rigid or jointed keel in conjunction with internal pressure in the gas containers and ballonets.

The term "airship" is sometimes incorrectly applied to heavier-than-air craft either in full or as "ship." This is a slang use of the word and should be avoided.

air speed — The speed of an aircraft relative to the air. Its symbol is V .

air-speed meter:

air-speed indicator — An instrument for indicating the speed of an aircraft relative to the air. It is actuated by the pressure developed in a suitable pressure nozzle or against a suitable obstruction and is graduated to give true air speed at a standard air density.

The speed indicated by the instrument is termed the "indicated air speed." (The indicated speed is a direct measure of the lift or drag exerted on the airplane at any altitude. Stalling at all altitudes occurs for the same value of the indicated speed.)

true air-speed meter — An instrument for measuring the true speed of an aircraft relative to the air. The Biram and Robinson anemometers are of this type.

airway — An air route between air traffic centers which is over terrain best suited for emergency landings, with landing fields at intervals equipped with aids to air navigation and a communication system for the transmission of information pertinent to the operation of aircraft.

The term "airway" may apply to an air route for either landplanes or seaplanes or both.

altigraph — An altimeter equipped with a recording mechanism. Present instruments are of the aneroid type. The chart, driven by clockwork, is usually graduated in feet or meters in accordance with some empirical or arbitrary pressure-temperature-altitude formula. In other words, it is a barograph whose scale is designed to read heights.

altimeter — An instrument for measuring or indicating the elevation of an aircraft above a given datum plane.

altimeter, aneroid — An altimeter, the indications of which depend on the deflection of a pressure-sensitive element. The graduations of the dial correspond to an empirical or arbitrary pressure-temperature-altitude formula.

altimeter, electrical-capacity — An altimeter, the indications of which depend on the variation of an electrical capacity with distance from the earth's surface.

altimeter, engine — An altimeter for indicating the altitude corresponding to the pressure produced in the intake manifold of a supercharged engine.

altimeter, optical — An altimeter, the indications of which depend on the manipulation of a suitable optical system.

altimeter, sound-ranging — An altimeter, the indications of which depend on the measurement of the time required for a sound wave to travel from the aircraft to the earth and back.

amphibian — An airplane designed to rise from and alight on either land or water.

anemometer — An instrument for indicating or measuring the speed of an air stream.

aneroid altimeter — See ALTIMETER, ANEROID.

angle, aileron — The angular displacement of an aileron from its neutral position. It is positive when the trailing edge of the aileron is below the neutral position.

angle, critical — An angle of attack at which the flow about an airfoil changes abruptly with corresponding abrupt changes in the lift and drag.

angle, downwash — The angle through which an air stream is de-

flected by any lifting surface of an airplane. It is measured in a plane parallel to the plane of symmetry and is denoted by the symbol ϵ .

angle, drift — The horizontal angle between the longitudinal axis of an aircraft and its path relative to the ground.

angle, effective helix — The angle of the helix described by a particular point on a propeller blade as the airplane moves forward through air otherwise undisturbed. It is equal to the angle whose tangent is the ratio of the velocity of flight to the product of the four quantities: 2π , r (the distance from the axis to the point in question) and n (the number of revolutions per second), i.e.,

$$\Phi = \tan^{-1}\left(\frac{V}{2\pi rn}\right).$$

angle, elevator — The angular displacement of the elevator from its neutral position. It is positive when the trailing edge of the elevator is below the neutral position.

angle, landing — The acute angle between the line of thrust of an airplane and the horizontal when the airplane is resting on level ground in its natural position. Also called "ground angle."

angle, longitudinal dihedral — The difference in angle of wing setting and of stabilizer setting. (This angle is positive when the angle of stabilizer setting, referred to the thrust line, is less than the angle of wing setting.)

angle, minimum gliding — The acute angle between the horizontal and the most nearly horizontal path along which an airplane can descend steadily in still air when the propeller is giving no thrust.

angle of attack — The acute angle between the chord of an airfoil and its direction of motion relative to the air. (This definition may be extended to other bodies than airfoils.) Its symbol is α .

angle of incidence of wing — See ANGLE OF WING SETTING.

angle of pitch — The acute angle between two planes defined as follows: One plane includes the lateral axis of the aircraft and the direction of the relative wind; the other plane includes the lateral axis and the longitudinal axis. (In normal flight the angle of pitch is, then, the angle between the longitudinal axis and the direction of the relative wind.) This angle is denoted by Θ and is positive when the nose of the aircraft has risen.

angle of roll, or angle of bank — The acute angle through which an aircraft must be rotated about its longitudinal axis in order to bring its lateral axis into a horizontal plane. This angle is de-

noted by Φ and is positive when the left wing is higher than the right.

angle of stabilizer setting — The acute angle between the line of thrust of an airplane and the chord of the stabilizer.

angle of wing setting. — The acute angle between the plane of wing chord and the line of thrust. It may differ for each wing.

angle of yaw — The acute angle between the direction of the relative wind and the plane of symmetry of an aircraft. This angle is denoted by Ψ and is positive when the aircraft has turned to the right.

angle, propeller-blade — The acute angle between the chord of a propeller section and a plane perpendicular to the axis of rotation of the propeller. Usually called "blade angle."

angle, rudder — The acute angle between the rudder and the plane of symmetry of the aircraft. It is positive when the trailing edge has moved to the left with reference to the normal position of the pilot.

angle, wing-dihedral or dihedral — The acute angle between the transverse reference line in the wing surface and the lateral axis of the airplane projected on a plane perpendicular to the longitudinal axis. The dihedral angle is positive when the upper obtuse angle for the two wings is less than 180° .

angle, zero-lift — The angle of attack of an airfoil when its lift is zero.

apron — A hard surface area of considerable extent immediately in front of the entrance of a hangar or aircraft shelter which is used for the handling of aircraft or for repair in clear weather.

aspect ratio — The ratio of span to mean chord of an airfoil; i.e., the ratio of the square of the maximum span to the total area of an airfoil.

aspect ratio of propeller blade — Half the ratio of propeller diameter to maximum blade width.

attitude — The position of an aircraft as determined by the inclination of its axes to some frame of reference. If not otherwise specified, this frame of reference is fixed to the earth.

aviation — The art of operating heavier-than-air craft.

axes of an aircraft — Three fixed lines of reference, usually centroidal and mutually perpendicular. The longitudinal axis in the plane of symmetry, usually parallel to the axis of the propeller, is called the longitudinal axis; the axis perpendicular to this in the plane of symmetry is called the normal axis; and the third axis perpendicular to the other two is called the lateral axis. In mathemati-

cal discussions, the first of these axes, drawn from front to rear, is called the *X* axis; the second, drawn upward, the *Z* axis; and the third, running from right to left, the *Y* axis.

balanced surface — A control surface which extends on both sides of the axis of the hinge or pivot in such a manner as to reduce the moment of the air forces about the hinge.

balloon — An aerostat without a propelling system.

barrage — A small captive balloon, used to support wires or nets which are intended as a protection against attacks by aircraft.

captive — A balloon restrained from free flight by means of a cable attaching it to the earth.

constant pressure ² — A supply balloon arranged to maintain a constant pressure of gas in a moored or docked aerostat.

free — A balloon, usually spherical, whose ascent and descent may be controlled by use of ballast or with a loss of the contained gas, and whose direction of flight is determined by the wind.

kite — An elongated form of captive balloon, fitted with lobes to keep it headed into the wind and usually deriving increased lift due to its axis being inclined to the wind.

nurse * — Sometimes used to refer to a constant-pressure balloon.

observation — A captive balloon used to provide an elevated observation post.

pilot * — A small balloon sent up to show the direction and speed of the wind.

propaganda — A small free balloon sent up without passengers but with a device by which papers or documents may be dropped at intervals.

sounding * — A small balloon sent up without passengers but with recording meteorological instruments.

supply * — A container made of heavy fabric employed as a portable means of storing gas at low pressure. It is usually too heavy to rise, even if free.

triangulation * — A small captive balloon used as a mark on which to sight in a triangulation survey.

bank — To incline an airplane laterally, i.e., to rotate it about its longitudinal axis. Right-bank is to incline the airplane with the right wing down.

Also used as a noun to describe the position of an airplane when its lateral axis is inclined to the horizontal.

bank, angle of — See ANGLE OF ROLL.

² Those forms of balloons marked with an asterisk (*) are not, strictly speaking, aircraft.

- barograph** — An instrument for recording the barometric or static pressure of the atmosphere.
- barrel-type engine** — See **ENGINE, BARREL-TYPE**.
- bay (body parts)** — The portion of a face of a truss, or of a fuselage, between adjacent bulkheads or adjacent struts or frame positions.
- biplane** — An airplane with two main supporting surfaces placed one above the other.
- blade back** — The side of a propeller blade which corresponds to the upper surface of an airfoil.
- blade face** — The surface of a propeller blade which corresponds to the lower surface of an airfoil. Sometimes called "thrust face," or "driving face."
- blade-width ratio** — The ratio of the developed width of a propeller blade at any point to the circumference of a circle whose radius is the distance of that point from the propeller axis.
- blimp** — A small nonrigid airship. "Airship" is to be preferred.
- body** — The fuselage or hull, or nacelle (including cowlings and covering) and nacelle mounting.
- bow-heavy** — The condition of an airship which, when at rest in still air, trims with its axis inclined down by the bow. The term "bow-heavy" is preferred to "nose-heavy" in describing airships.
- brake mean effective pressure** — The net unit pressure which, if applied during the power strokes to the pistons of an engine having no mechanical losses, would produce the given brake horse power at the stated speed.
- cabane** — A framework for supporting the wings at the fuselage; also applied to the system of trussing used to support overhang in a wing.
- camber** — The rise in the curve of an airfoil section from its chord, usually expressed as the ratio of the departure of the curve from the chord to the length of the chord. "Upper camber" refers to the upper surface of an airfoil and "lower camber" to the lower surface; "mean camber" is the mean of these two.
- ceiling:**
- absolute** — The maximum height above sea level at which a given airplane would be able to maintain horizontal flight, assuming standard air conditions.
- service** — The height above sea level, assuming standard air conditions, at which a given airplane ceases to be able to rise at a rate higher than a small specified one (100 feet per minute in the

United States and England). This specified rate may be different in different countries.

ceiling, static — The altitude in standard atmosphere, at which an aerostat is in static equilibrium after removal of all dischargeable weights.

center of pressure coefficient — The ratio of the distance of the center of pressure from the leading edge to the chord length.

center of pressure of an airfoil section — The point in the chord of an airfoil section, prolonged if necessary, which is at the intersection of the chord and the line of action of the resultant air force. Its abbreviation is *C. P.*

chord (of an airfoil section) — The line of a straight edge brought into contact with the lower surface of the section at two points; in the case of an airfoil having double convex camber, the straight line joining the leading and trailing edges. (These edges may be defined, for this purpose, as the two points in the section which are farthest apart.)

The line joining the leading and trailing edges should be used also in those cases in which the lower surface is convex except for a short flat portion.

The method used for determining the chord should always be explicitly stated for those sections with regard to which ambiguity seems likely to arise.

chord length — The length of the projection of the airfoil section on its chord. Its symbol is *c*.

chord, mean, of a combination of wings — The ratio—

$$\frac{c_1 S_1 + c_2 S_2 + c_3 S_3 + \dots}{S_1 + S_2 + S_3 + \dots}$$

where c_1, c_2, c_3 , etc., are the mean chords of various wings, and S_1, S_2, S_3 , etc., are their areas.

chord, mean of a wing — The quotient obtained by dividing the wing area by the extreme dimension of the wing projection at right angles to the chord.

climb, rate of — See RATE OF CLIMB.

cloth — Fabric delivered by the bleachery or finisher before it has been proofed, doped, or specially treated for aeronautic use.

cockpit — The open spaces in which the pilot and passengers are accommodated. When the cockpit is completely housed in, it is called a cabin.

compass, induction — A compass, the indications of which depend on the current generated in a coil revolving in the earth's magnetic field.

controllability — The quality in an airplane which makes it possible for the pilot to change its attitude easily and with the exertion of but little force.

controls — A general term applied to the means provided to enable the pilot to control the speed, direction of flight, attitude, and power of an aircraft.

air controls — The means employed to operate the control surfaces of the aircraft.

engine controls — The means employed to control the power output of the engines. (Control of speed may be effected by the air controls or the engine controls independently, or by either in conjunction with the other.)

control stick — The vertical lever by means of which the longitudinal and lateral controls of an airplane are operated. Pitching is controlled by a fore-and-aft movement of the stick, rolling by a side-to-side movement.

control surface — See SURFACE, CONTROL.

cowling — A removable covering which extends over or around the engine, and sometimes over a portion of the fuselage or nacelle as well.

critical angle — See ANGLE, CRITICAL.

critical speed — See SPEED, CRITICAL.

cross-country flight — See FLIGHT, CROSS-COUNTRY.

cross-wind force — See FORCE, CROSS-WIND.

dead load — See WEIGHT, EMPTY, which is to be preferred.

decalage — The acute angle between the wing chords of a biplane or multiplane.

dihedral angle — See ANGLE, WING-DIHEDRAL.

dirigible — That can be directed; steerable; as a dirigible balloon. Its use as a noun to indicate an airship is improper.

dive — A steep descent, with or without power, in which the air speed is greater than the maximum speed in horizontal flight.

divergence — A motion in which, after a disturbance from equilibrium, the body departs continuously, without oscillations, from its original state of motion.

dope (airplane) — The liquid material applied to the cloth surfaces of airplanes to increase strength, to produce tautness by shrinking, and to act as a filler for maintaining air-tightness.

dope (pigmented) — An aircraft dope to which a pigment has been added to make an opaque finish, or to protect it from the effects of sunlight.

downwash angle — See ANGLE, DOWNWASH.

drag — The component parallel to the relative wind of the total air force on an aircraft or airfoil. Its symbol is D .

The "absolute drag coefficient" is C_D as defined by the equation

$C_D = \frac{D}{qS}$, in which D is the drag, q is the impact pressure

($= \frac{1}{2} \rho V^2$) and S is the effective area of the surface upon which the air force acts.

In the case of an airplane, that part of the drag due to the wings is called "wing drag"; that due to the rest of the airplane is called "structural drag" or "parasite resistance."

induced — That portion of the wing drag induced by, or resulting from, the generation of the lift.

profile — That portion of the wing drag which is due to friction and turbulence in the fluid and which would be absent in a nonviscous fluid.

drift — The lateral velocity of an aircraft due to air currents.

drift angle — See **ANGLE**, **DRIFT**.

drift bar — A part of a drift meter or other instrument for indicating the apparent direction of motion of the ground relative to the fore-and-aft axis of the aircraft. It usually consists of a wire or arm which can be set along this direction of motion. Cf. **drift**.

drift meter — An instrument for measuring the angle between the fore-and-aft axis of an aircraft and its path over the ground. One form consists of a drift bar provided with a suitable angular scale. (Cf. **drift**.) The instrument is graduated to read correctly when it is level.

D-ring — A ring having (as the name implies) the shape of a capital D , to which rope suspensions are attached.

dry weight of an engine — See **ENGINE**, **DRY WEIGHT OF**.

duralumin — An alloy of aluminum which is much used in aeronautics, especially for the structure of airships and airplanes. Its chemical composition and physical properties are about as follows:

Copper, 3.5 to 4.5 per cent.

Manganese, 0.4 to 1 per cent.

Magnesium, 0.2 to 0.75 per cent.

Aluminum, 92 per cent., minimum.

Tensile strength, ultimate, 55,000 pounds per square inch.

Tensile strength at elastic limit, 30,000 pounds per square inch.

Elongation of 2 inches at ultimate strength (test specimen $\frac{1}{2}$ inch wide), 18 per cent.

Specific gravity not more than 2.85.

dynamic factor — The ratio between the load carried by any part of an aircraft when accelerating and the corresponding basic load.

dynamic lift — See **LIFT, DYNAMIC**.

dynamic load — See **LOAD, DYNAMIC**.

dynamic (or impact) pressure — The product $\frac{1}{2} \rho V^2$, where ρ is the density of the air and V is the relative speed of the air. It is the quantity measured by most air-speed instruments. Symbol is q .

economic speed — See **SPEED, ECONOMIC**.

effective helix angle — See **ANGLE, EFFECTIVE HELIX**.

effective thrust — See **THRUST, EFFECTIVE**.

elevator — A movable auxiliary airfoil, the function of which is to impress a pitching moment on the aircraft. The elevator is usually hinged to the stabilizer.

elevator angle — See **ANGLE, ELEVATOR**.

engine altimeter — See **ALTIMETER, ENGINE**.

engine, barrel-type — An engine having its cylinders arranged equidistant from and parallel to the main shaft.

engine controls — See **CONTROLS**.

engine, dry weight of an — The weight of the engine, including carburetor and ignition systems complete, propeller hub assembly, reduction gears, if any, but excluding exhaust manifolds, oil, and water. If the starter is built into the engine as an integral part of the structure its weight shall be included.

engine, inverted — An engine having its cylinders below the crankshaft.

engine, left-hand — An engine whose propeller shaft, to an observer facing the propeller from the antipropeller end of the shaft, rotates in a counterclockwise direction.

engine, radial — An engine having stationary cylinders arranged radially around a common crankshaft.

engine, right-hand — An engine whose propeller shaft, to an observer facing the propeller from the antipropeller end of the shaft, rotates in a clockwise direction.

engine, rotary — An engine having revolving cylinders arranged radially around a common fixed crankshaft.

engine, supercharged — An engine with mechanical means for increasing the cylinder charge beyond that normally taken in at the existing atmospheric pressure and temperature.

engine, vertical — An engine having its cylinders arranged vertically above the crankshaft.

engine, V-type — An engine having its cylinders arranged in two rows, forming, in the end view, the letter "V."

engine, W-type — An engine having its cylinders arranged in three rows, forming, in the end view, the letter "W." Sometimes called the "broad-arrow type."

entering edge — See LEADING EDGE.

envelope — The outer covering of an aerostat, usually of fabric. It may or may not be also the gas container. It may be divided by diaphragms into separate gas compartments or cells, and it may also contain internal air cells or ballonets.

factor, dynamic — See DYNAMIC FACTOR.

factor of safety — The ratio of the ultimate strength of a member to the maximum probable load in that member in actual use.

fairing — An auxiliary member or structure whose primary function is to reduce head resistance or drag of the part to which it is fitted (without, in general, contributing strength).

fairing wire — See WIRE, FAIRING.

fin — A fixed surface, attached to a part of the aircraft, parallel to the longitudinal axis, in order to secure stability; for example, tail fin, skid fin, etc. Fins are sometimes adjustable.

fin carrier — See CARRIER, FIN.

fire wall — A fire-resistance transverse bulkhead, so set as to isolate the engine compartment from the other parts of the structure and thus to reduce the risk from fire in the engine compartment.

fitting — A generic term for any small part used in the structure of an airplane or airship. If without qualification, a metal part is usually understood. It may refer to other parts, such as "fabric fittings."

fixed fuel tank — See TANK, FIXED FUEL.

fixed power-plant weight for a given airplane — See WEIGHT, FIXED, POWER-PLANT, FOR A GIVEN AIRPLANE.

fixed surface — See FIN.

fixed weight — See WEIGHT, FIXED (AIRSHIP).

flight, cross-country — A flight which necessitates leaving the vicinity of a regular landing field.

flight indicator — See INDICATOR, FLIGHT.

flight path — The path of the center of gravity of an aircraft with reference to the earth.

flight recorder — See RECORDER, FLIGHT.

float — A completely inclosed water-tight structure attached to an aircraft in order to give it buoyancy and stability when in contact with the surface of the water. In float seaplanes the crew

is carried in a fuselage or nacelle separate from the float. The term "pontoon" is now obsolete.

flotation gear — See GEAR, FLOTATION.

flying boat — A form of seaplane supported, when resting on the surface of the water, by a hull or hulls providing flotation in addition to serving as fuselages. For the central hull type, lateral stability is usually provided by wing-tip floats. The term "boat seaplane" is now obsolete.

force, cross-wind — The component, perpendicular to the lift and to the drag, of the total air force on the aircraft or any part thereof. Its symbol is C and its absolute coefficient C_C is defined by

$$C_C = \frac{C}{qS}$$

where q is the impact pressure ($= \frac{1}{2}\rho V^2$) and S is the effective area of the surface upon which the air force acts.

fuel (or oil) consumption, specific — The weight of fuel (or oil) consumed per brake horsepower-hour.

fuel tank, fixed — See TANK, FIXED FUEL.

full load — See LOAD, FULL.

fuselage — The structure, of approximately streamline form, to which are attached the wings and tail unit of an airplane. In general it contains the power plant, passengers, cargo, etc.

fuselage, monocoque — A type of fuselage construction wherein the structure consists of a thin shell of wood, metal, or other material, supported by ribs, frames, belt frames, or bulkheads, but usually without longitudinal members other than the shell itself. The whole is so disposed as to carry the stresses to which the structure is subjected.

gap — The distance between the planes of the chords of any two adjacent wings, measured along a line perpendicular to the chord of the upper wing at any designated point of its leading edge. Its symbol is G .

gear, flotation — An emergency gear attached to a landplane to permit alighting on the water and to provide buoyancy when resting on the surface of the water.

glide — A descent with reference to the air at a normal angle of attack and without engine power sufficient for level flight in still air, the propeller thrust being replaced by a component of gravity along the line of flight. Also used as a verb.

glider — A form of aircraft similar to an airplane, but without a power plant.

ground angle — See **ANGLE, LANDING**.

ground speed — See **SPEED, GROUND**.

ground-speed meter — An instrument for measuring the speed of an aircraft relative to the ground. In present types of instruments some reference line in the instrument must first be set parallel to the apparent direction of motion of the aircraft with reference to the ground before the speed measurement is made. This is usually accomplished by the use of a drift meter, the adjustment of which automatically orients the ground-speed meter properly. Thus both the magnitude and direction of the motion of the aircraft with reference to the ground are obtained.

gyroscopic turn indicator — See **INDICATOR, GYROSCOPIC TURN**.

hangar — A shelter for housing aircraft. More properly applied to heavier-than-air craft.

helicopter — A form of aircraft whose sole support in the air is derived directly from the vertical component of the thrust produced by rotating airfoils.

horsepower of an engine, maximum — The maximum horsepower which an engine can develop.

horsepower of an engine, rated — The average horsepower developed by an engine of a given type in passing the standard 50-hour endurance test.

hull (seaplane) — The portion of a flying boat which furnishes buoyancy when in contact with the surface of the water. It contains accommodations for the crew and passengers, usually incorporating the functions of a float and fuselage in one unit.

impact pressure — See **DYNAMIC (OR IMPACT) PRESSURE**.

inclinometer — An instrument for indicating the attitude of an aircraft. Inclinometers are termed fore-and-aft, lateral, or universal, according as they indicate inclination on the vertical plane through the fore-and-aft axis, or in the vertical plane through the lateral axis, or in both planes, respectively.

inclinometer, absolute — An instrument which indicates the attitude of an aircraft with reference to the vertical. The indications of instruments of this type usually depend on gyroscopic action.

inclinometer, relative — An instrument which indicates the attitude of an aircraft with reference to apparent gravity, i.e., to the resultant of the acceleration of the aircraft and that due to gravity.

indicator, air-speed — See **AIR-SPEED METER**.

indicator, ballonnet-fullness — An instrument for indicating the volume of air in a ballonnet.

- indicator, flight** — An instrument in which a lateral inclinometer, a fore-and-aft inclinometer, and a turn indicator are combined to form a compact unit.
- indicator, gyroscopic turn** — A turn indicator dependent on gyroscopic action.
- indicator, pitch** — An instrument for indicating the existence of a pitching velocity of an aircraft. Cf. turn indicator.
- indicator, static turn** — A turn indicator actuated by the difference in pressure between static tubes mounted near the wing tips equidistant from the plane of symmetry and in a plane parallel to the lateral axis.
- indicator, turn** — An instrument for indicating the existence of an angular velocity of turn of an aircraft about the normal axis. In horizontal flight it indicates the presence of a yawing velocity. "Turn meter" is the term applied to certain types.
- indraft (inflow)** — The flow of air from in front of the propeller into the blades.
- induced drag** — See DRAG, INDUCED.
- induction compass** — See COMPASS, INDUCTION.
- inflow** — See INDRAFT.
- inverted engine** — See ENGINE, INVERTED.
- kite** — An aircraft heavier than air, restrained by a tow-line and sustained by the relative wind.
- kymograph** — An instrument for recording the angular oscillations of an aircraft in flight with respect to axes fixed in space. The reference direction is usually given by a gyroscope or a beam of sunlight.
- laminated wood** — See WOOD, LAMINATED.
- landing angle** — See ANGLE, LANDING.
- landing field** — A field of such a size and nature as to permit of aircraft landing and taking off in safety. It may or may not be part of an airport.
- landing gear** — The understructure which supports the weight of an aircraft when in contact with the surface of the land or water and reduces the shock on landing. There are five common types — boat type, float type, skid type, wheel type, and ski type. (Amphibian may be a combination of the float or boat type with wheels or skis.)
- landing speed** — See SPEED, LANDING.
- landing T** — A large symbol shaped like a capital T which is laid out on a landing field or on the top of a building to guide operators of aircraft in landing and taking off.

landing wire — See WIRE, LANDING.

landplane — An airplane designed to rise from and alight on the land.

leading edge — The foremost edge of an airfoil or propeller blade.
Also called "entering edge."

left-hand engine — See ENGINE, LEFT-HAND.

left side (engine) — That side which, to an observer looking from the antipropeller end toward the propeller end, lies on the left-hand side.

lift — That component of the total air force on an aircraft or airfoil which is perpendicular to the relative wind and in the plane of symmetry. It must be specified whether this applies to a complete aircraft or to parts thereof. In the case of an airship, this is often called "dynamic lift." Its symbol is L .

The "absolute lift coefficient" is C_L as defined by the equation

$$C_L = \frac{L}{qS}$$

in which L is the lift, q is the impact pressure ($= \frac{1}{2}\rho V^2$) and S is the effective area of the surface upon which the air force acts.

lift (of a gas) — The difference of density of air and the gas. Both supposed to be under the same conditions of pressure, temperature, etc.

lift, dynamic — The lift impressed on an aerostat by aerodynamic forces.

lift, gross (airship) — The lift obtained from a volume of buoyant gas equal to the nominal gas capacity of the aircraft. Obtained by multiplying the nominal gas capacity by the lift per unit volume of the gas used for inflation.

lift, static (aerostat) — The resultant upward force on an aerostat at rest obtained by multiplying the actual volume of the air displaced by the density of the air and subtracting the weight of the contained gas. (The volume of the air displaced, multiplied by the difference of density of the air and the contained gas.)

lift, useful (airship) — The lift available for carrying fuel, and oil, passengers, cargo, food, and drinking water, guns, ammunition, and bombs. Usually determined by deducting from the gross lift all fixed weights; certain allowances of ballast, fuel, and oil; water; spares and tools; crew and equipment. No standard has as yet been established.

load:

dead — See WEIGHT, EMPTY.

full — Weight empty plus useful load. Also called "gross weight."

- pay** — That part of the useful load from which revenue is derived, viz., passengers and freight.
- useful** — The crew and passengers, oil, and fuel, ballast other than emergency, ordnance, and portable equipment.
- load, basic** — The load on an aircraft when it is at rest or in a condition of unaccelerated rectilinear flight. (For purposes of stress analysis.)
- load, dynamic** — Any load due to accelerations of an aircraft, and therefore proportional to its mass.
- load factor** — The ratio of any specified load on a member to the corresponding basic load. Generally applied to the ratio of the breaking load to a basic load.
- loading, power** — The gross weight of an airplane, fully loaded, divided by the normal brake horsepower of the engine computed for air of standard density unless otherwise stated.
- loading, wing** — The gross weight of an airplane, fully loaded, divided by the area of the supporting surface. The area used in computing the wing loading should include ailerons, but not the stabilizer and elevators.
- longeron** — A fore-and-aft member of the framing of an airplane fuselage or nacelle, usually continuous across a number of points of support.
- longitudinal dihedral angle** — See ANGLE, LONGITUDINAL DIHEDRAL.
- main supporting surface** — See SURFACE, MAIN SUPPORTING.
- maneuverability** — That quality in an aircraft which makes it possible for the pilot to change its attitude rapidly.
- meter, air-speed** — See AIR-SPEED METER.
- meter, ground-speed** — See GROUND-SPEED METER.
- meter, superheat** — An instrument for measuring the difference in temperature between the gas in a gas container of a lighter-than-air craft and the surrounding air.
- minimum gliding angle** — See ANGLE, MINIMUM GLIDING.
- minimum speed** — See SPEED, MINIMUM.
- monocoque fuselage** — See FUSELAGE, MONOCOQUE.
- monoplane** — An airplane which has but one main supporting surface, sometimes divided into two parts by the fuselage.
- multiplane** — An airplane with two or more main supporting surfaces placed one above another.
- nacelle** — An inclosed shelter for passengers or for a power plant. A nacelle is usually shorter than a fuselage, and does not carry the tail unit.
- nose-heavy** — The condition of an airplane in normal flight when

the distribution of forces is such that, if the longitudinal controls were released, the nose would drop.

nozzle, pressure — An instrument which, in combination with a gauge, is used to measure the indicated speed of an aircraft relative to the air. It may be a Pitot-static or a Venturi tube, or a combination of a Pitot tube and a Venturi tube.

optical altimeter — See ALTIMETER, OPTICAL.

ornithopter — A form of aircraft heavier than air, deriving its chief support and propelling force from flapping wings.

oscillation, phugoid — A long-period oscillation characteristic of the disturbed longitudinal motion of an aircraft. This is referred to when it is said that an aircraft "hunts."

oscillation, stable — An oscillation whose amplitude does not increase.

oscillation, unstable — An oscillation whose amplitude increases continuously until an attitude is reached from which there is no tendency to return toward the original attitude, the motion becoming a steady divergence.

over-all length — The distance from the extreme front to the extreme rear of an aircraft, including the propeller and the tail unit.

overhang — Used in two senses. (1) One-half of the difference in span of any two main supporting surfaces of an airplane. The overhang is positive when the upper of the two main supporting surfaces has the larger span. (2) The distance from the outer strut attachment to the tip of the wings.

pancake, to — To level off an airplane at a greater altitude than normal in a landing, thus causing it to stall and to descend on a steeply inclined path with the wings at a very large angle of attack and without appreciable bank.

panel (wing parts) — Where a wing surface comprises several units of construction, these units are designated as panels.

parasite resistance — See DRAG.

pay load — See LOAD, PAY.

performance testing — See TESTING, PERFORMANCE.

period — The time taken for a complete oscillation.

phugoid oscillation — See OSCILLATION, PHUGOID.

pilot — An operator of aircraft. This term is applied regardless of the sex of the operator.

pitch, angle of — See ANGLE OF PITCH.

pitch indicator — See INDICATOR, PITCH.

pitch of a propeller:

effective — The distance which an aircraft advances along its flight path for one revolution of the propeller. Its symbol is p_e .

- geometrical** — The distance which an element of a propeller would advance in one revolution, if it were moving along a helix of slope equal to its blade angle.
- mean geometrical** — The mean of the geometrical pitches of the several elements. Its symbol is p_g .
- standard** — The geometrical pitch taken at two-thirds of the radius. Also called "nominal pitch." Its symbol is p_s .
- zero thrust** — The distance which a propeller would have to advance in one revolution in order that there might be no thrust. Also called "experimental mean pitch." Its symbol is p_v .
- zero torque** — The distance which a propeller would have to advance in one revolution in order that the torque might be zero. Its symbol is p_a .
- pitch ratio** — The ratio of the pitch (geometrical, unless otherwise stated) to the diameter p/D .
- pitch speed** — The product of the mean geometrical pitch by the number of revolutions of the propeller in unit time — i.e., the speed the aircraft would make if there were no slip.
- Pitot tube** — A cylindrical tube with an open end which is pointed upstream (i.e., so that the air meets the instrument head-on or is met head-on by the instrument). When the aircraft is flying less than about 200 miles per hour, the instrument measures the impact pressure. When used on aircraft, it is usually associated either with a closed coaxial tube surrounding it or with a closed tube placed near it and parallel to it, the combination being termed a Pitot-static tube. The associated tube has perforations in its side so that it is subjected to static pressure, as distinct from impact pressure. The speed of the fluid can be determined from the difference between the impact pressure and the static pressure as read by a suitable gauge. In common terminology the Pitot-static combination, as above, is often termed simply a Pitot tube or Pitot.
- pontoon (now obsolete)** — See FLOAT.
- power loading** — See LOADING, POWER.
- pressure, dynamic** — See DYNAMIC (OR IMPACT) PRESSURE.
- pressure nozzle** — See NOZZLE, PRESSURE.
- pressure tube** — See TUBE, PRESSURE.
- profile** — See AIRFOIL SECTION (OR PROFILE).
- profile drag** — See DRAG.
- propeller:**
- adjustable pitch** — A propeller whose blades are so attached to the hub that they may be set to any desired pitch when the propeller is stationary.

controllable pitch or variable pitch — A propeller whose blades are so mounted that they may be turned about their axis to any desired pitch while the propeller is in rotation.

propeller area, projected — The total area in the plane perpendicular to the propeller shaft swept by the propeller, excepting the portion covered by the boss and that swept by the root of the blade. This portion is usually taken as extending 0.2 of the maximum radius from the axis of the shaft.

propeller blade — See **BLADE FACE**; **BLADE BACK**; **BLADE-WIDTH RATIO**.

propeller-blade angle — See **ANGLE, PROPELLER-BLADE**.

propeller-blade area — The area of the blade face, exclusive of the boss and the root, i.e., of a portion which is usually taken as extending 0.2 of the maximum radius from the axis of the shaft.

propeller boss — The central portion of a propeller in which the hub is formed or mounted.

propeller-camber ratio — The ratio of the maximum thickness of a propeller section to its chord.

propeller-disk area, total — The total area swept by a propeller, i.e., the area of a circle having a diameter equal to the propeller diameter.

propeller efficiency — The ratio of thrust power to power input of a propeller. Its symbol is η .

propeller hub — The metal fitting inserted or incorporated in or with a propeller for the purpose of mounting it on the propeller or engine shaft.

propeller interference — The amount by which the torque and thrust of a propeller are changed by the modification of the air flow in the slip stream produced by bodies placed near the propeller, such as engine, radiator, etc.

propeller-load curve — A curve representing the engine power necessary to drive any given propeller at various speeds. The power required varies approximately as the cube of the speed in R.P.M.,

provided the ratio $\frac{V}{ND}$ remains constant.

propeller pitch — See **PITCH OF A PROPELLER**.

propeller, pusher — A propeller mounted to the rear of the engine or propeller shaft. (It is usually behind the wing cell or nacelle.)

propeller rake — The mean angle which the line joining the centroids of the sections of a propeller blade makes with a plane perpendicular to the axis.

- propeller reinforcing girder** — See GIRDER, PROPELLER REINFORCING.
- propeller root** — That part of the propeller blade near the boss.
- propeller section** — A cross section of a propeller blade made at any point by a plane parallel to the axis of rotation of the propeller and tangent at the centroid of the section to an arc drawn with the axis of rotation as its center.
- propeller thrust** — The component parallel to the propeller axis of the total air force on the propeller. Its symbol is T .
- propeller torque** — The moment applied to the propeller by the engine shaft. Its symbol is Q .
- propeller, tractor** — A propeller mounted on the forward end of the engine or propeller shaft. (It is usually forward of the fuselage or wing nacelle.)
- propeller-width ratio, total** — The product of blade-width ratio at the point of maximum blade width by number of blades.
- propulsive efficiency** — The ratio of the product of effective thrust and flight speed to the actual power input to the propeller as mounted on the airplane, consistent units being used throughout.
- pusher airplane** — See AIRPLANE, PUSHER.
- pusher propeller** — See PROPELLER, PUSHER.
- quadruplane** — An airplane with four main supporting surfaces, placed one above another.
- race rotation** — The rotation, produced by the action of the propeller, of the stream of air passing through or influenced by the propeller.
- radial engine** — See ENGINE, RADIAL.
- rake, propeller** — See PROPELLER RAKE.
- range at economic speed** — The maximum distance a given aircraft can cover while cruising at the most economical speed and altitude at all stages of the flight.
- range at full speed** — The maximum distance a given aircraft can cover at full speed at sea level.
- rate of climb** — The vertical component of the air speed of an aircraft, i.e., its vertical velocity with reference to the air.
- recorder, flight** — An instrument for recording certain elements of the performance of an aircraft.
- relative inclinometer** — See INCLINOMETER, RELATIVE.
- relative wind** — See WIND, RELATIVE.
- resistance derivatives** — Quantities expressing the variation of the forces and moments on aircraft due to disturbance of steady motion. They form the experimental basis of the theory of

stability, and from them the periods and damping factors of aircraft can be calculated. In the general case there are 18 translatory and 18 rotary derivatives.

lateral — Resistance derivatives expressing the variation of moments and forces due to small changes in the lateral, yawing, and rolling velocities.

longitudinal — Resistance derivatives expressing the variation of moments and forces due to small changes in the longitudinal, normal, and pitching velocities.

rotary — Resistance derivatives expressing the variation of moments and forces due to small changes in the rotational velocities of the aircraft.

translatory — Resistance derivatives expressing the variation of moments and forces due to small changes in the translational velocities of the aircraft.

restoring moment — See **RIGHTING MOMENT**.

reverse turn — See **TURN, REVERSE**.

revolutions, maximum, — The number of revolutions per minute corresponding to the maximum horsepower.

revolutions, rated — The number of revolutions corresponding to the rated horsepower.

Reynolds Number — A name given the fraction $\rho \frac{Vl}{\mu}$ in which

ρ is the density of the fluid;

V is the relative velocity of the fluid;

l is the linear dimension of the body;

μ is the coefficient of viscosity of the fluid.

rigger — One who is employed in assembling and aligning aircraft.

rigging (airplane) — The assembling, adjusting, and aligning of the parts of an airplane.

right-hand engine — See **ENGINE, RIGHT-HAND**.

righting moment (or restoring moment) — A moment which tends to restore an aircraft to its previous attitude after any small rotational displacement.

right side (engine) — That side which, to an observer looking from the antipropeller end toward the propeller end, lies on the right-hand side.

roll — A maneuver in which a complete revolution about the longitudinal axis is made, the horizontal direction of flight being approximately maintained.

roll, angle of — See **ANGLE OF ROLL**.

rotary engine — See **ENGINE, ROTARY**.

rudder — A movable auxiliary airfoil, the function of which is to impress a yawing moment on the aircraft in normal flight. It is usually located at the rear of an aircraft.

rudder angle — See **ANGLE, RUDDER**.

rudder bar — The foot bar by means of which the control cables leading to the rudder are operated.

rudder torque — The twisting moment exerted by the rudder on the fuselage. The product of the rudder area by the distance from its center of area to the axis of the fuselage may be used as a relative measure of rudder torque.

safety, factor of — See **FACTOR OF SAFETY**.
load in that member in actual use.

seaplane — Any airplane designed to rise from and alight on the water. This general term applies to both boat and float types, though the boat type is usually designated as a "flying boat."

service tank — See **TANK, SERVICE**.

ship — Slang for an airplane. In view of the confusion with "airship" it should not be used.

shipplane — A landplane designed to rise from and alight on the deck of a ship.

shock absorber — A device incorporated in the landing gear of an aircraft to reduce the shock imposed on the structure when alighting or taking off.

Shock absorbing devices are usually interposed between the main structure and the wheels, floats, skis, or tail skids, to secure resiliency in landing and taxiing.

side slipping — Flight in which the lateral axis is inclined and the airplane has a component of velocity in the direction of the lower end of the lateral axis. When it occurs in connection with a turn, it is the opposite of skidding. (q. v.)

skid — A runner used as a member of the landing gear and designed to aid the aircraft in landing or taxiing.

tail skid — A skid used to support the tail when in contact with the ground.

wing skid — A skid placed near the wing tip and designed to protect the wing from contact with the ground.

skidding — Sliding sidewise away from the center of curvature when turning. It is usually caused by banking insufficiently, and is the opposite of side slipping. (q. v.)

skid fin — A fore-and-aft vertical surface, usually placed above the upper wing, designed to provide vertical keel surface and so to increase lateral stability.

skin friction — The tangential component of the fluid force at a point on a surface.

sky writing — The act of emitting from an aircraft a trail of smoke or other visible substance, the flight of the aircraft being so directed as to cause the trail to assume the form of letters or symbols.

slip — The difference between the mean geometrical pitch and the effective pitch. Slip may be expressed as a percentage of the mean geometrical pitch or as a linear dimension.

slip fuel tank — See TANK, SLIP FUEL.

slip function — The ratio of speed of advance through the undisturbed air to the product of propeller diameter by the number of

revolutions in unit time, i.e., $\frac{V}{ND}$. The slip function is the

primary factor controlling propeller performance. It is π times the ratio of forward speed to the tip speed of the propeller.

slip stream — The stream of air driven astern by the propeller. (The indraft is sometimes included also.)

soar — To perform sustained free flight without self-propulsion; it is called "up-current soaring" if performed in ascending air; "dynamic soaring" in other cases.

sound-ranging altimeter — See ALTIMETER, SOUND-RANGING.

span (airfoil) — The lateral dimension of an airfoil, i.e., its dimension perpendicular to its chord. Its symbol is b .

span (airplane) — The maximum distance measured parallel to the lateral axis from tip to tip of an airplane inclusive of ailerons.

spar — See WING SPAR.

specific fuel (or oil) consumption — See FUEL (OR OIL) CONSUMPTION, SPECIFIC.

speed, critical — The lowest speed of an aircraft at which control can be maintained.

speed, economic — The speed at which the fuel consumption, per unit of distance covered in still air, is a minimum.

speed, ground — The horizontal component of the velocity of an aircraft relative to the earth.

speed, landing — The minimum speed at which an airplane can maintain itself in level flight and still be under adequate control.

speed, minimum — The lowest steady speed which can be maintained by an airplane in level flight at an altitude large in comparison with the dimensions of the wings, with any throttle setting whatever.

spin — A maneuver consisting of a combination of roll and yaw, with the longitudinal axis of the airplane inclined steeply downward. The airplane descends in a helix of large pitch and very small radius, the upper side of the airplane being on the inside of the helix, and the angle of attack on the inner wing being maintained at an extremely large value.

spinner — A fairing of approximately conical or paraboloidal form, which is fitted coaxially with the propeller boss and revolves with the propeller.

spiral — A maneuver in which an airplane descends in a helix of small pitch and large radius, the angle of attack being within the normal range of flight angles.

spiral instability — See **STABILITY**.

stability — That property of a body which causes it, when disturbed from a condition of equilibrium or steady motion, to develop forces or moments which tend to restore the body to its original condition.

automatic — Stability dependent upon movable control surfaces automatically operated by mechanical means.

inherent — Stability of an aircraft due solely to the disposition and arrangement of its fixed parts, i.e., that property which causes it, when disturbed, to return to its normal attitude of flight without the use of controls or the interposition of any mechanical devices.

static — Stability of such a character that, if the airplane is displaced slightly from its normal attitude by rotation about an axis through its center of gravity (as may be done in wind-tunnel experiments), moments come into play which tend to return the airplane toward its original attitude.

dynamic — Stability of such a character that, if the airplane is displaced from steady motion in flight, it tends to return to that steady state of motion, the oscillations due to restoring moments being damped out.

In a general way, the difference between static stability and dynamic stability is that the former depends on restoring moments alone, while the latter includes the action of damping factors.

longitudinal — Stability with reference to disturbances in the plane of symmetry, i.e., disturbances involving pitching and variation of the longitudinal and normal velocities.

directional — Stability with reference to rotations about the normal axis, i.e., an airplane possesses directional stability in its simplest

form if a restoring moment comes into action when it is given a small angle of yaw. Owing to symmetry, directional stability is closely associated with lateral stability.

lateral — Stability with reference to disturbances involving rolling, yawing, or side slipping, i.e., disturbances in which the position of the plane of symmetry of the aircraft is affected.

spiral instability — A type of instability inherent in certain airplanes which becomes evident when the airplane, as a result of a yaw, assumes too great a bank and side slips; the bank continues to increase and the radius of the turn to decrease.

stabilizer — A normally fixed airfoil whose function is to lessen the pitching motion. It is usually located at the rear of an aircraft and is approximately parallel to the plane of the longitudinal and lateral axes. Also called "tail plane."

stabilizer (aerostat) — Same as **FIN**. The lobes of a kite balloon are sometimes referred to as stabilizers.

stabilizer, mechanical — A mechanical device to prevent an aircraft from departing from a condition of steady motion, or, in case such a motion is disturbed, to restore it to its steady state. Includes gyroscopic stabilizers, pendulum stabilizers, inertia stabilizers, etc.

stabilizer setting, angle of — See **ANGLE OF STABILIZER SETTING**.

stable oscillation — See **OSCILLATION, STABLE**.

stagger — The amount of advance of the leading edge of an upper wing of a biplane, triplane, or multiplane over that of a lower, expressed either as a percentage of gap or in degrees of the angle whose tangent is the percentage just referred to. It is considered positive when the upper wing is forward and is measured from the leading edge of the upper wing along its chord to the point of intersection of this chord with a line drawn perpendicular to the chord of the upper wing at the leading edge of the lower wing, all lines being drawn in a plane parallel to the plane of symmetry.

stall — The condition of an airplane when from any cause it has lost the air speed necessary for support or control.

static ceiling — See **CEILING, STATIC**.

static lift — See **LIFT, STATIC (AEROSTAT)**.

static thrust — See **THRUST, STATIC**.

static trim — See **TRIM, STATIC**.

static turn indicator — See **INDICATOR, STATIC TURN**.

statoscope — An instrument for detecting minute changes of altitude of an aircraft. The indications of the instrument usually depend on small changes of the static pressure of the air.

- stay** — A wire or other tension member; for example, the stays of the wing and body trussing.
- step** — A break in the form of the bottom of a float or hull designed to reduce resistance when under way by rapidly reducing the wetted surfaces as speed increases. It also serves to eliminate suction effects.
- stern-heavy** — The condition in which, in normal flight, the after end of an airship tends to sink and which requires correction by means of the horizontal controls. In this condition an airship is said to "trim by the stern." It may be due to either aerodynamic or static conditions, or to both.
- streamline** — The path of a small portion of a fluid relative to a solid body with respect to which the fluid is moving. The term is commonly used only of such flows as are not eddying, but the distinction should be made clear by the context.
- streamline flow** — Steady flow past a solid body, i.e., a flow in which the direction at every point is independent of time.
- streamline form** — A solid body which produces approximately streamline flow.
- structural drag** — See DRAG.
- strut** — A compression member of a truss frame. For instance, the vertical members of the wing truss of a biplane (interplane struts) and the short vertical and horizontal members separating the longerons (q. v.) in the fuselage.
- strut, drag** — A fore-and-aft compression member of the internal bracing system of a wing.
- supercharged engine** — See ENGINE, SUPERCHARGED.
- supercharger** — A mechanical device for supplying the engine with a greater weight of charge than would normally be induced at the prevailing atmospheric pressure and temperature.
- centrifugal type** — A supercharging device equipped with one or more rotating impellers generating centrifugal force which is utilized for the compression and the transmission of the air against resistance.
- positive-driven type** — A supercharger driven at a fixed speed ratio from the engine shaft by gears or other positive means.
- rotary-blower type** — A supercharging device comprising one or more relatively slow-speed rotors revolving in a stationary case in such a way as to provide a positive displacement.
- turbo type** — A supercharger driven by a turbine operated by the exhaust gases from the engine.
- supporting surface, main** — See SURFACE, MAIN SUPPORTING.

surface, control — A movable airfoil designed to be rotated or otherwise moved by the pilot in order to change the attitude of the airplane or airship.

surface, fixed — See **FIN**.

surface, main supporting — A set of wings, extending on the same general level from tip to tip of an airplane; e.g., a triplane has three main supporting surfaces. The main supporting surfaces include the ailerons, but no other surfaces intended primarily for control or stabilizing purposes.

sweep back — The acute angle between the lateral axis of an airplane and the projection of the axis of the wing on the plane which includes the lateral and longitudinal axes. (The axis of a wing is a line through the centroids of the section of the wing.)

tail group (or tail unit) — The stabilizing and control surfaces at the rear end of an aircraft, including stabilizer, fin, rudder, and elevator. (Also called "empennage.")

tail-heavy — In a heavier-than-air craft, the condition in which in normal flight, the tail sinks if the longitudinal control is released, i.e., the condition in which the pilot has to exert a push on the control stick to keep the given attitude.

tail-heavy (airship) — See **STERN-HEAVY**.

tail plane — See **STABILIZER**.

tail skid — See **SKID**.

tail slide — The backward and downward motion, tail first, which certain airplanes may be made to take momentarily after having been brought into a stalling position by a steep climb.

tandem airplane — See **AIRPLANE, TANDEM**.

tank, fixed fuel — A fuel tank which is not intended or fitted to be dropped, as "slip" tanks are.

tank, service — A fixed fuel tank near each power unit, into which fuel from other tanks is pumped and from which the fuel supplying the engines is drawn.

tank, slip fuel — A fuel tank which is provided with a device permitting the quick dropping of the tank and contents as a whole in case of an emergency. Fitted on both airships and airplanes.

taxi — To run an airplane over the ground, or a seaplane on the surface of water under its own power.

testing, performance — The process of determining performance characteristics.

thermograph — An instrument for recording temperature.

thrust, effective — The net driving force delivered by a propeller when mounted on an airplane, i.e., the actual thrust given by the

propeller, as mounted on the airplane, minus any increase of resistance of the airplane produced by the action of the propeller.

thrust face — See **BLADE FACE**.

thrust, static — The thrust developed by a propeller when rotating at a fixed point.

tipping (propeller) — A sheet-metal (or equivalent) protective covering of the blade of a propeller near the tip, extended a short distance along the trailing edge and a considerable distance along the leading edge.

total propeller-width ratio — See **PROPELLER-WIDTH, TOTAL**.

tractor airplane — See **AIRPLANE, TRACTOR**.

tractor propeller — See **PROPELLER, TRACTOR**.

trailing edge — The rearmost edge of an airfoil or propeller blade.

triplane — An airplane with three main supporting surfaces, placed one above another.

turn indicator — See **INDICATOR, TURN**.

turn, reverse — A rapid maneuver to reverse the direction of flight of an airplane, made by a half loop and half roll.

unstable oscillation — See **OSCILLATION, UNSTABLE**.

Venturi, power — A Venturi tube used to operate gyroscopic turn indicators and other instruments.

Venturi, speed-indicating — A Venturi tube may be combined with a Pitot tube or with a tube giving static pressure to form a pressure nozzle which may be used to determine the indicated speed of an aircraft through the air. The pressure difference is measured by a suitable gauge.

Venturi tube — A short tube with flaring ends and a narrow or constricted section between them, into which a side tube opens. When fluid flows through the Venturi, there is a reduction of pressure in the constricted section, the amount of the reduction being a function of the velocity of flow.

vertical engine — See **ENGINE, VERTICAL**.

vertimeter — A device for indicating the rate of rise and fall of an aerostat, usually a special form of statoscope. A rate-of-climb meter serves the same purpose, although of a different form.

V-type engine — See **ENGINE, V-TYPE**.

warp — To change the form of a wing by twisting it. Warping is sometimes used to maintain the lateral equilibrium of an airplane.

wash — The disturbance in the air produced by the passage of an airfoil. Also called the "wake" in the general case for any solid body.

washin — Permanent warping of the wing which results in an increase in the angle of attack near the tip.

- washout** — Permanent warping of a wing which results in a decrease in the angle of attack near the tip.
- weight, empty** — The structure, power plant, and fixed equipment of an aircraft. Included in this fixed equipment are the water in the radiator and cooling system, all essential instruments and furnishings, fixed electric wiring for lighting, heating, etc. In the case of the aerostat the amount of ballast which must be carried to assist in making a safe landing must also be included.
- weight, fixed power-plant, for a given airplane** — The weight of an engine, including ignition, carburetor, and induction systems complete, propeller and hub, exhaust manifolds, radiator and water, *if used*, with all interconnecting wires, controls, tanks, and pipes, lubricating-oil temperature regulators, *the oil contained in the engine crankcase* and the starting gear attached to the engine, but excluding fuel, oil, and engine instruments.
- weight per horsepower** — The dry weight of an engine divided by the rated horsepower.
- wind, relative** — The motion of the air with reference to a body, i.e., its motions are observed by a man at rest on the body. The direction and velocity of the relative wind, therefore, are found by adding two vectors, one being the velocity of the air with reference to the earth, the other being equal and opposite to the velocity of the body with reference to the earth.
- wind tunnel** — An elongated chamber, usually a tube divergent at the ends, through which a steady air stream may be drawn or forced. Models of airfoils, of aircraft, or of propellers may be placed in the middle portion of the tunnel, called the experiment chamber or working section, and supported by suitable balances placed outside the air stream, so that the forces, moments, etc., due to the moving air may be measured.
- wing** — A general term applied to a whole or a portion of the main supporting surfaces of an airplane, but in the latter case is usually qualified as right wing, left wing, upper wing, or lower wing, etc.
- wing-dihedral angle** — See ANGLE, WING-DIHEDRAL OR DIHEDRAL.
- wing drag** — See DRAG.
- wing-heavy** — The condition of an airplane in which (in normal flight) there is a tendency for the right (or left) wing to drop, if the lateral control is released, i.e., the condition in which the pilot has to exert a lateral force on the control stick to keep the lateral axis horizontal.
- wing loading** — See LOADING, WING.
- wing rib** — A fore-and-aft member of the wing structure of an airplane, used to give the wing section its form and to transmit the load from the fabric to the spars.

- rib compression** — A heavy rib designed to have the function of a wing rib and also to act as a strut opposing the pull of the wires in the internal drag-truss. (Also called "Drag strut.")
- rib, former or false** — An incomplete rib, frequently consisting only of a strip of wood extending from the leading edge to the front spar, which is used to assist in maintaining the form of the wing where the curvature of the airfoil section is sharpest.
- wing setting, angle of** — See ANGLE OF WING SETTING.
- wing skid** — See SKID.
- wing spar** — The principal transverse structural member of the wing assembly of an airplane.
- wing truss** — The framing by which the wing loads of an airplane are transmitted to the fuselage. It comprises struts, wires, cables, tie rods, and spars.
- wire** — In aeronautics, refers specifically to drawn solid wire.
- wire, drag** — Any wire or cable designed primarily to resist drag forces.
- internal** — A drag wire concealed inside the wing.
- external** — A drag wire run from a wing to the fuselage or other part of the airplane.
- wire, landing** — A wire designed primarily to resist forces in the opposite direction to the normal direction of the lift and to oppose the lift wire and prevent distortion of the structure by an over-tightening of those members. Sometimes called "antilift" wire.
- wire, lift** — A wire or cable which transmits the lift on the outer portion of the wing of an airplane in toward the fuselage or nacelle. This wire usually runs from the top of an interplane strut to the bottom of the strut next nearer the fuselage. Sometimes called "flying wire."
- wire, stagger** — A wire connecting the upper and lower surfaces of an airplane and lying in a plane substantially parallel to the plane of symmetry. (Also called "incidence wire.")
- W-type engine** — See ENGINE, W-TYPE.
- yaw, angle of** — See ANGLE OF YAW.
- yawmeter** — An instrument for measuring the angle of yaw.
- zero-lift angle** — See ANGLE, ZERO-LIFT.
- zero-lift line** — A line through the trailing edge of an airfoil section parallel to the direction of the wind when the lift is zero.
- zoom** — To climb for a short time at an angle greater than that which can be maintained in steady flight, the airplane being carried upward at the expense of its kinetic energy. This term is sometimes used as a noun, to denote any sudden increase in the upward slope of the flight path.

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